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THESIS

PERFORMANCE-BASED DESIGN FOR ARSON THREATS: POLICY ANALYSIS OF THE PHYSICAL SECURITY FOR FEDERAL FACILITIES STANDARD

by

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To assess the effectiveness of the permanent countermeasures options provided in the *Physical Security Criteria for Federal Facilities*, a performance-based approach to evaluating the design and construction features is recommended. Clearly articulated performance objectives and quantifiable characterization of the hazardous elements comprising the threat scenarios are essential to evaluating outcomes using a performance-based design approach.

A mixed methods research approach is used to analyze the *Physical Security Criteria for Federal Facilities* standard to make policy recommendations that may enhance occupant safety and federal property protection from arson attacks. Computerized fire effects modeling is used to compare outcomes in non-military and non-postal federal facilities from a variety of simulated arson scenarios using commonly available accelerants.

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PERFORMANCE-BASED DESIGN FOR ARSON THREATS: POLICY ANALYSIS OF THE PHYSICAL SECURITY FOR FEDERAL FACILITIES STANDARD

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LIST OF ACRONYMS AND ABBREVIATIONS

AE	Anticipated, expected
ALF	Animal Liberation Front
ANFO	Ammonium nitrate-Fuel Oil
ASET	Available Safe Egress Time
ASTM	ASTM International[1]
BATFE	Bureau of Alcohol, Tobacco, Firearms and Explosives
BEU	Beyond Extremely Unlikely
BSC	Building Security Committee
Btu	British Thermal Unit
C	Celsius
cal	Calorie
CBR	Chemical, Biological or Radioactive
CBRN	Chemical, Biological, Radioactive, or Nuclear
CBRNE	Chemical, Biological, Radioactive, Nuclear, or Explosive
CCTV	Closed Circuit Television
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
COG	Continuity of Government
COOP	Continuity of Operations Plan
CUI	Controlled, Unclassified Information
DBT	Design-Basis Threat
DHS	Department of Homeland Security
DOE	Department of Energy
DOJ	Department of Justice
EC_{50}	Effective Concentration (at 50% of maximum effect)
ELF	Earth Liberation Front
EO	Executive Order
EU	Extremely Unlikely
F	Fahrenheit
FBI	Federal Bureau of Investigation
FDS	Fire Dynamics Simulator
FEMA	Federal Emergency Management Agency
FOSM	First-order second- moment
FOUO	For Official Use Only
FPS	Federal Protective Service

[1] Formerly the American Society for Testing and Materials.

FSC	Facility Security Committee
FSL	Facility Security Level
g	Gram
GAO	Government Accountability Office[2]
gpm	Gallons Per Minute
GPRA	Government Performance and Results Act of 1993
GSA	General Services Administration
ΔH_c	Heat of Combustion
HCN	Hydrogen Cyanide
Hg	Mercury (chemical symbol)
HRR	Heat Release Rate
HSPD	Homeland Security Presidential Directive
HVAC	Heating, Ventilation and Air Conditioning
I&A	Infrastructure and Analysis
ICC	International Code Council
IED	Improvised Explosive Device
IID	Improvised Incendiary Device
ISC	Interagency Security Committee
ISO	International Organization for Standardization
Kg	Kilogram
kJ	Kilojoules
kJ/g	Kilojoules per Gram
kW	Kilowatts
L	Liter
lb	Pound
LC_{50}	Lethal Concentration (at 50% of maximum effect)
LOP	Level of Protection
lpm	Liters Per Minute
m	Meter
mJ	Millijoule
mL	Milliliter
MW	Megawatt
N	Total Number of Cases
n	Sub-total Number of Cases
NA	Not Applicable
NFA	National Fire Academy

[2] Before 2002, GAO was known as the General Accounting Office. See 31 U.S.C. § 702.

NFDC	National Fire Data Center
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
NIBRS	National Incident-Based Reporting System
NIPP	National Infrastructure Protection Plan
NIST	National Institute of Standards and Technology
NR	Not Reported
NRC	National Research Council of the National Academy of Science
NRCC	National Research Council of Canada
oz	Ounce (avoirdupois)
Pa	Pascal
P100	Facilities Standards for the Public Buildings Service (P100)
PBD	Performance-Based Design
PBS	Public Buildings Service
PMMA	Polymethyl Methacrylate
ppmv	Parts per million (volume)
PVC	Polyvinyl Chloride
RSET	Required Safe Egress Time
RTI	Response Time Index
SCADA	Supervisory Control and Data Acquisition
SD	Standard Deviation
SFPE	Society of Fire Protection Engineers
SI	International System of Units
sq. in.	Square Inch(es)
t	Time
TNT	Trinitrotoluene
TSA	Transportation Security Administration
U	Unclassified
Unl	Unlikely
UCR	Uniform Crime Reports
UK	United Kingdom
UL	Underwriters Laboratories
U.S.	United States
USC	United States Code
USFA	United States Fire Administration
USMS	United States Marshals Service
VBIED	Vehicle-Borne Improvised Explosive Device
W	Watt

Yr	Year
$\geq$	Greater than or equal to
$\leq$	Less than or equal to
$=$	Equal to
$\cdot$	Multiplied by

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I. INTRODUCTION

The federal government is the largest real property manager in the United States. Overall, it owns or leases more than 3.34 billion square feet (3.10296×10^{8} m^2) of property among 429,000 buildings used by 24 government agencies[3] (U.S. General Services Administration, 2010b). To provide tenants, workers, residents, and visitors a degree of protection from threats to their health, safety, and welfare while they occupy these structures, these buildings are required by federal law to meet minimum construction standards.

In the United States, federal building design and construction for the last 50 years were based on prescriptive standards. While these regulations generally have served well in protecting occupants and buildings, the changing nature of adversaries and their tactics demands a new approach to federal asset protection. In 1995, the federal government began a transition to risk-based security planning and decision making to protect public buildings. That transition can be enhanced to meet dynamic threats by embracing the precepts of performance-based design.

A. PROBLEM STATEMENT

Most contemporary U.S. building designs are *prescriptive*, in that they must comply with specific safety rules and features prescribed within building codes. Although codes do not specify how buildings are designed, they limit architectural options. Designers must comply with a stringent framework of regulations that do not address specific threats nor provide predictable or measurable outcomes in response to specific threats or vulnerabilities. Why are prescriptive designs a problem? They offer generic solutions that may not adequately address the overall threats, vulnerabilities, risks, and hazards needed to create a resilient facility.

[3] This study is limited to the approximately 9,000 non-military, non-postal buildings controlled by the General Services Administration.

Following the April 20, 1995, domestic terrorist bombing of the Alfred P. Murrah Building in Oklahoma City, the U.S. Department of Justice was tasked to assess the vulnerability of federal office facilities to terrorism and acts of violence. A series of subsequent federal efforts have developed a risk-based model to assess and improve facility security. The *Physical Security Criteria for Federal Facilities* (2010) employs a risk-based approach to assign permanent countermeasures to a variety of pre-scripted adversarial and terrorist threat scenarios. Once the security threat level is established through a ranking protocol, the risk-based model directs the tenant Facility Security Committee (FSC) to select permanent countermeasures from a table of prescriptive options intended to minimize risk, or the FSC may simply accept the risk. The mix of performance-based risk assessment and prescriptive solutions is irrational.

Risk includes the probability of an event and its impact. To evaluate risk adequately, threats, vulnerabilities, and consequences must be quantified. The Interagency Security Committee (ISC) *Design-Basis Threat* (DBT) and *Physical Security Criteria for Federal Facilities* standards are policy documents that describe 31 different terrorist scenarios and provide limited design options to address each one. In a few cases, the asymmetric threat scenarios are clearly articulated and quantified so a physical security specialist could develop meaningful countermeasures. For example, the scenario for a mailed or delivered explosive device states the device likely will "be packaged in a large, padded shipping enveloped or small box containing not less than 100 grams of TNT[4] or TNT equivalent" (U.S. Department of Homeland Security, 2010c). Knowing the size of the explosive component, a physical security specialist can assess the impact of the shock wave, its travel distance, its velocity, and the likelihood of death, injury, and damage within a certain radius of the device.

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[4] Tri-nitro-toluene, a common high explosive.

The *Physical Security Criteria for Federal Facilities'* pre-scripted threat scenarios include this one for arson:[5] "An adversary places an improvised incendiary device (IID) containing an accelerant and utilizing a delay mechanism adjacent to a facility, but outside the view of security countermeasures." While this covert threat may sound dramatic, it is ill defined and not measurable. The size of the device, the physical and chemical nature of the accelerant, the volume or weight of the accelerant, the distance from the facility, and the facility type of construction are not defined; therefore, a meaningful risk assessment cannot be performed and suitable permanent countermeasures cannot be identified and applied. A performance-based design method would allow the security team to define a range of threats, assess their potential effects, and evaluate specific countermeasures most suited to address them.

Arson is a security and terrorist threat to federal buildings and facilities in the United States. According to Baird (2006), "historical analysis of incidents coupled with open source information reveals that terrorist groups in general are adapting toward simple destructive methods like arson with increasingly high levels of fatalities" (p. 416). As recently as May 31, 2012, the Department of Homeland Security National Operations Center issued a warning that:

> International terrorist groups and violent extremists have long shown interest in using fire as a weapon due to the low cost and limited technical expertise required, the potential for causing large-scale damage, and the low risk of apprehension. Recent encouragement of use of this tactic by terrorist groups and violent extremists in propaganda materials and extremist web forums is directed at Western audiences and supports Homeland attacks. (U.S. Department of Homeland Security Office of Intelligence and Analysis, 2012, p. 2)

On February 14, 2012, a homeland security fusion center reported intelligence that an alleged member of an Iraqi terrorist organization was plotting to burn Federal Emergency Management Agency buildings throughout the United States (Maryland

[5] Arson is a common law term that describes the crime of using fire to injure persons or damage property. In the fire protection field, "incendiarism" defines the act of intentional fire setting regardless of criminal intent. Since the ISC uses the term arson to describe intentionally set fires, it is used synonymously with incendiarism in this thesis.

Coordination and Analysis Center, 2012). Overall, arson in the United States accounted for an estimated 210,300 intentionally set fires each year from 2004 to 2006, the most recent years for which data is available. Intentionally set fires accounted for 13% of fires reported by fire departments in the United States. These fires resulted in an average of approximately 375 deaths, 1,300 injuries, and $1.06 billion in property loss each year (U.S. Fire Administration, 2009). In non-military and non-postal federally owned or leased properties alone, from 2008 to 2010, 51 structural fires caused $10,647,586 in damage. More than 5% of these fires were attributed to arson or domestic terrorist attack (J. Elvove, personal communication, May 10, 2011). Table 1 provides a summary of the fire incident data reported to the General Services Administration (GSA) in non-military and non-postal federal facilities[6] during that period.

Table 1. Fire Incidents: GSA Federal Facilities: 2008–2010 (From: J. Elvove, personal communication, May 10, 2011)

	Year				
Property type	**2010**	**2009**	**2008**	**Total**	**% Total**
Office	14	14	16	44	80.0
Courthouse	0	1	5	6	10.9
Retail space	0	0	1	1	1.8
Mobile[a]	1	2	1	4	7.3
Total	15	17	23	55	100.0

[a]Mobile properties include mobile equipment: movable under its own power, or towed, such as an airplane, automobile, boat, cargo trailer, farm vehicle, motorcycle, or recreational vehicle, and are outside the scope of this study.

The predominant cause of fires in these facilities was some sort of electrical problem: faulty wiring, poor maintenance, or improperly used equipment. Table 2 provides a breakdown by ignition source of the structural fires reported to the GSA during the 2008–2010 period.

[6] The Administrator of GSA is responsible for the construction and maintenance of non-military and non-postal federal facilities. See 40 U.S.C. § 3302 (2010) and 40 U.S.C. § 581 (2010).

Table 2. Fire Causes: GSA Federal Facilities: 2008–2010 (From: J. Elvove, personal communication, May 10, 2011)

	Year				
Ignition source	**2010**	**2009**	**2008**	**Total**	**% Total**
Arson/incendiary	0	1	1	2	3.6
Cooking	0	0	4	4	7.3
Electrical lighting/equipment	12	11	13	36	65.5
Welding/cutting	1	1	2	4	7.3
Domestic terror attack[a]	1	0	0	1	1.8
Other	1	4	3	8	14.5
Total	15	17	23	55	100.0

Note. Data includes mobile properties.
[a]Private airplane flown into office building, Austin, Texas, February 18, 2010.

Despite the fact the data overwhelmingly shows that in the 2008–2010 timeframe the leading cause of fire in non-military, non-postal federal buildings was some sort of electrical malfunction, concern exists regarding malicious acts against federal properties. According to the ISC DBT, the baseline threat to federal facilities from the described IID event is assessed to be high (U.S. Department of Homeland Security, 2010c).

For the purpose of this study, no distinction occurs between the use of the terms fire and arson. Fire is a complex chemical reaction generally involving a fuel, an oxidizing agent, and a competent heat source, and arson is a legal term to describe a criminal act—the consequence of which is a fire or explosion. Fires may occur as the result of a natural event, such as a lightning strike in light grassy fuels, or as the unintentional result of a mechanical malfunction, such as overheating equipment or an electrical spark. Likewise, fires can result from human error, such as discarding burning debris or by misusing of flammable products around heat sources. The outcome of unintentional fires or those intentionally set may be the same: unwanted heat, smoke, property damage, injury, or death.

While improvised explosive devices (IED) often are the primary focus of federal security professionals trying to protect assets from a terrorist attack, a direct link does

exist between IED and fire. The instantaneous oxidation that occurs when an IED explodes is the same chemical reaction that occurs in a fire; only the speed with which the chemical reaction and ensuing shock wave occur are different. Furthermore, the instantaneous oxidation of an IED may be the trigger for a secondary, firebomb-type device. The car bomb parked May 2, 2010 by Faisal Shahzad in New York City's Times Square contained 10 gallons (37.8 L) of gasoline and three 25-pound (23.6 L) liquefied petroleum gas cylinders. According to Williams and Dienst (2010), while a test conducted by the Federal Bureau of Investigation's (FBI) Operational Technology Division could not calculate the firebomb's exact explosive force, its effects likely would have killed scores of people.

A second shortcoming of the *Physical Security Criteria for Federal Facilities* approach is its emphasis on threats it calls "primarily manmade." According to the report, "other threats to buildings, such as earthquakes, fire, or storms are beyond the scope of this document and are addressed in *applicable construction standards* [italics added], although many of the countermeasures identified will contribute to mitigating natural hazards" (U.S. Department of Homeland Security, 2010c). This approach presumes the applicable construction standards—the model building codes—are adequate to protect against these and other natural hazards. Many technological hazards—such as fires, gas leaks, and other hazardous materials releases—are both manmade and an equal or greater threat than terrorist attacks. To provide comprehensive physical security for federal facilities, all hazards and threats should be addressed by the nature of the destructive potential.

B. RESEARCH QUESTIONS

1. Primary Research Question

How can the U.S. Department of Homeland Security (DHS) ISC *Physical Security Criteria for Federal Facilities* standard employ performance-based design methods to evaluate the effectiveness of its permanent countermeasure options to arson threats?

2. Secondary Research Questions

How can the arson threat scenario described in the DBT be quantified for the purposes of selecting permanent countermeasures?

Are the design methods published in the Society of Fire Protection Engineers (SFPE) *SFPE Engineering Guide to Performance Based Fire Protection* or the International Code Council (ICC) *Performance Code for Buildings and Facilities* suitable tools to evaluate permanent countermeasure options to quantified arson threats?

Should the ISC reports *Physical Security Criteria for Federal Facilities* and the DBT be limited to criminal or manmade threats as stated in the documents?

C. HYPOTHESIS

DHS ISC was created to produce physical security standards for non-military and non-postal federal facilities. It has developed a risk-based analytical approach to assess the protection of federal employees and property from manmade threats. The approach is intended to give in situ FSC members a means to evaluate the level of protection needed based on an assessment of the facility's overall vulnerability to one or more threats. While the risk-based approach employs an easy-to-follow process, some threat scenarios do not provide enough information to permit a rational evaluation of the outcome.

The ISC DBT and *Physical Security Criteria for Federal Facilities* standards are policy documents that describe a condensed description of 31 different threat scenarios and provide limited design solutions to address each one. In some cases, the threat scenarios are clearly articulated and quantified so a physical security specialist could develop meaningful countermeasures. In the arson scenario, the description is so vague that threat-specific countermeasures cannot be developed.

Arson as a means of attack on federal facilities remains a vulnerability that should be addressed in federal construction practices to minimize hazards to occupants' lives, damage to taxpayer-owned property, and the interruption of essential government services. Current building and fire codes are predicated on a single fire event that occurs

in or near a structure, and built-in fire protection features are expected to control the fire to a reasonable degree. An arsonist armed with large quantities of highly flammable materials—or one who manages to set multiple fires within or near a structure—creates events not anticipated in contemporary codes and construction methods. Specific countermeasures—based on the anticipated threat—are needed to provide successful event outcomes as defined by those affected.

In its assessment of the arson threat, the DBT cites Federal Bureau of Investigation Uniform Crime Reporting data and DHS' Federal Protective Service (FPS) records that indicate from 2007 through 2010, nine arson cases were reported at approximately 9,000 GSA properties.[7] While the scale and history have not been significant, the DBT acknowledges the arson threat to federal facilities is viable.

> Based on the unsophisticated nature of the attack, availability of specific information on planning and executing such an attack, the historical frequency of its use in general and specifically against Federal facilities, and demonstrated intent by terrorist organizations to utilize this tactic against Federal facilities, the baseline threat to Federal facilities is assessed to be **HIGH** [emphasis in original text]. (U.S. Department of Homeland Security, 2010c)

Terrorist and adversarial threats are dynamic; perpetrators probe to find weaknesses in security plans and countermeasures. Threats and tactics change over time. Improvised weaponry evolves over time and becomes more sophisticated and harder to detect. Even technological hazards—dismissed in the *Physical Security Criteria for Federal Facilities* as beyond the scope of the document—change with growth in technology, industry, and markets. Using design-basis threat scenarios that lead to a limited number of permanent countermeasure options is shortsighted and contrary to meaningful security. If the *Physical Security Criteria for Federal Facilities* standard and its supporting DBT were amended to employ performance-based design methods using quantified arson threats, then threat-specific permanent countermeasures could be defined to mitigate the consequences.

[7] Chapter VII addresses vagaries in data collection and reporting.

An analysis of these two ISC policies will reveal that their current design-basis and permanent countermeasure strategies do not provide facility security, architecture, or design teams meaningful criteria against which a proposed design can be measured. The policies are lacking fundamental criteria to explain the differences among arson attack methods, the nature of the potential weaponry, the potential for damage, and the effectiveness of the countermeasures included as design options in the standards that should be employed.

As a result of the policy analysis, it is anticipated that recommendations will be made to adopt one or more elements of the performance-based design methods of the SFPE or ICC used to address specific fire problems that start with the quantification of the potential fire threat and developing scientific and engineering-based design solutions to control or mitigate the event. The analysis may reveal that performance-based design methods could be applied to the other 30 threat scenarios described in the DBT.

The opportunity exists from this research to influence the application of a policy that addresses threat quantification among all the 31 design scenarios. Each of the scenarios could provide measurable parameters that would allow physical security specialists to assess the threat fully.

D. METHOD

The development of federal administrative policies is a complex process involving many—and sometimes competing—interests. The creation of the *Physical Security Criteria for Federal Facilities* standard was the work of participants from more than 20 agencies representing law enforcement, building construction and management, security, diplomacy, intelligence, education, human health, finance, and environmental protection. Given the range of professional disciplines involved, traditional quantitative or qualitative research methods may not fully address the breadth, complexity, and synergy of this effort. To get a more complete picture to perform better policy analysis, a variety of research methods are desirable.

Bardach (2009) described the evolving nature of policy analysis where the traditional image of the policy wonk buried deep in a bureaucracy producing periodic and detailed reports for decision makers has been replaced by policy analysts who work in cross-agency teams in loose networks that cut across organizational lines, which is precisely how the *Physical Security Criteria for Federal Facilities* standard was developed.

An evolving research method is applicable to evaluate this multi-discipline product, which is mixed methods research. Johnson and Onwuegbuzie (2004) defined mixed methods research as “the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study” (p. 17). They further stated that the goal of mixed methods research is not to replace either quantitative or qualitative research approaches, but to “draw from the strengths and minimize the weaknesses of both in single research studies and across studies” (pp. 14–15). Greene, Caracelli, and Graham (1989) reported that one of the five primary reasons for employing mixed methods research was triangulation, which is the comparison of findings from different methods to interpret the phenomenon under study.

The policy outcome to address these aforementioned shortcomings of prescriptive design solutions may be to adopt and apply the methods of performance-based design for fire safety. Performance-based design employs a rigorous multi-step system that articulates the desired performance end-state (the anticipated level of protection from the threat), and, using scientific and engineering tools, offers design options to achieve it. Performance-based design methods also embrace stakeholder accountability from programmatic concept, through design and construction, to implementation, and ultimately, to on-going maintenance. Stakeholders, both the Federal Security Committee and tenants, play a key role in defining and solving the desired end-state.

The policy analysis approach was selected to dissect and evaluate the existing policy (the *Physical Security Criteria for Federal Facilities* standard and its supporting DBT with the intent of identifying potential shortcomings and improvements during the

validation period. Policy analysis is expected to explore several ISC self-acknowledged shortcomings, as well as weaknesses in the use of the arson design basis threat currently specified in the document. Policy analysis will compare the methods described in the two documents to methods employed in the developing field of performance-based design.

The policy analysis approach will examine a number of the assumptions that underlie the problem statement. The most important consideration is that without clearly articulated design parameters, a desired end-state (level of protection) cannot be identified, nor its risk measured. Importing a poorly defined threat into a risk analysis model prevents its users from developing measurable outcomes.

To supplement the analysis, two prototypical facility scenarios are created representing federal facility configurations, and the designs are subjected to simulated fires using state-of-the-art fire modeling software. The model results are compared and evaluated for performance with the expectation that the current DBT arson scenario is unsatisfactory to achieve meaningful permanent countermeasures.

E. RESEARCH SIGNIFICANCE

This thesis serves to fill a gap in the literature pertaining to the application of performance-based design for federal facilities, with the potential for transfer to other government and private sector real property. Much of the literature on performance-based design is anticipatory as to how performance-based design approaches might be used, but the United States still has minimal experience with the method as a means of building design, construction, and performance evaluation.

Furthermore, this thesis serves as a foundation for additional research in the application of performance-based design to terrorist and criminal threats other than arson, a number of which are articulated in the DBT. By being able to quantify the scale, scope, and potential outcomes of various threat(s), the design and engineering community can strive to develop measurable protective strategies and designs to mitigate the threat and consequences.

The changing nature of terrorist tactics and threats—as well as those dismissed as manmade—requires a robust method that can evaluate the efficacy of proposed countermeasures for facility safety before they are implemented at sometimes significant costs to taxpayers. As such, this thesis may be useful to the DHS ISC, the GSA and other federal agencies that acquire, construct, or substantially remodel real property.

F. CHAPTER OVERVIEW

Following this introduction, Chapter II reviews recent literature pertaining to federal facility protection, federal construction regulations, performance-based design and building construction, computerized fire models, and the policy implications of performance-based design.

Chapter III explains the history of the development of the DHS ISC as it has evolved from the 1995 Department of Justice courthouse and office building vulnerability study to where it has come in 2012.

Chapter IV discusses the modern history of building and fire codes in the United States to provide the context for the differences between prescriptive and performance-based codes, and how their features can be exploited to achieve desirable design and safety goals.

Chapter V describes fire physics and behavior to provide a foundational understanding of the inputs used in the fire modeling analysis.

Chapter VI explains how fire has been used as a weapon, and the impact of potential IID and accelerants on the built environment.

Chapter VII describes the mixed method research approach, including the methods employed. It also includes the foundational data and findings that enable the policy analysis of the *Physical Security Criteria for Federal Facilities* standard and its supporting DBT.

Chapter VIII provides the analysis and recommendations of these documents to determine whether the DHS ISC *Physical Security Criteria for Federal Facilities* standard can employ performance-based design methods to evaluate the effectiveness of its permanent countermeasure options to arson threats.

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II. LITERATURE REVIEW

Research and writing about the protection of buildings from natural and manmade threats has a long history and a substantial body of literature ranging from architectural and engineering design through legally mandated construction regulations. Federally owned properties, because of their unique exempt legal status related to state and local building codes (based on the supremacy clause of the U.S. Constitution), are enjoined by the federal government's own guidelines. The application of performance-based design methods to federal properties offers architects and tenants alike a contemporary means for evaluating building safety. This section reviews recent literature on construction guidance and the elements of performance-based fire safe building design.

A. FEDERAL FACILITY PROTECTION

The acquisition, management, and protection of federal real property predate the founding of the republic. According to Kane, Anzovin, and Podell (1998), the first building erected in the United States for public use by the federal government was a brick structure for the U.S. Mint built on Seventh Street in Philadelphia. David Rittenhouse, director of the Mint, laid the cornerstone on July 31, 1792.

The literature related to the construction and protection of federal facilities is vast, which ranges from federal laws through agency policy to administrative implementation guidelines. In the context of this study, the literature related to physical security and fire protection in the modern era begins with the Federal Property and Administrative Services Act of 1949 (40 U.S.C § 101 *et. seq*.). This law applies to the acquisition and management of property held by most government agencies and assigns responsibility for real property to the Administrator of General Services. Numerous agencies, such as the Department of Defense, the United States Coast Guard, the National Aeronautical and Space Administration, both houses of Congress, and the White House, are among many

of the agencies exempt from the act (U.S. Government Accountability Office, 2003). See Appendix C for the definition of public buildings, the scope of the Federal Property and Administrative Services Act of 1949, and exceptions from it.

In 1992, the U.S. Congress amended the Federal Fire Safety Act to require automatic fire sprinkler systems or an equivalent level of safety in all new or significantly remodeled six story or taller federal office buildings (Boucher, 1992). Congress also required the GSA to develop regulations to define the term “equivalent level of safety” (15 U.S.C. § 2227 (d)). The eventual result was that designers were given three options to prove their proposal met an equivalent level of safety to a building with a complete automatic sprinkler system based on the building occupants’ ability to evacuate in a safe manner. In the first two alternatives, a measurable margin of safety[8] would be used to determine the acceptability of the alternate design. The first option required that proposed alternate designs provide available safe egress times equal to those in a building provided with complete automatic sprinkler protection. The second option—recommended for typical office scenarios—required the designer to predict the estimated times that a fire would reach flashover,[9] would produce a heat release rate (HRR) of 1,000 kilowatts[10] (1 MW), or leave the room where the fire began. The shortest of the three times would provide the baseline for available escape time. If the combination of proposed fire protection alternatives provided an adequate safety margin, that arrangement could be considered an equivalent level of safety. Finally, the third option allowed the government to accept other technical analysis procedures as long as they were conducted in accordance with recognized engineering standards (U.S. General Services Administration, 1994).

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[8] The margin of safety is measured as the difference between available safe egress time and required safe egress time. “Available safe egress time is the time available for evacuation of occupants to an area of safety prior to the onset of untenable conditions in occupied areas or the egress pathways. The required safe egress time is the time required by occupants to move from their positions at the start of the fire to areas of safety” (U.S. General Services Administration, 1994, p. 52).

[9] The point at which a rapid change occurs in a developing room or compartment fire to full involvement.

[10] HRR is a measure of the energy released over time by a burning object. A 1,000-kilowatt HRR is approximately equivalent to the energy emitted from a fully burning upholstered chair.

Stroup (1998) used performance-based design and fire modeling techniques to evaluate the relative safety of two federal building projects, and found that while the proposed designs enhanced occupant safety, additional research was necessary to support the use of performance-based design as a means to provide an equivalent level of safety.

Six weeks after al Qaeda operatives attacked the World Trade Center with aircraft, President George W. Bush began issuing a series of Homeland Security Presidential Directives (HSPD) on matters pertaining to homeland security. On December 13, 2003, the President issued HSPD 7 “Critical Infrastructure[11] Identification, Prioritization, and Protection” that included a requirement that “all Federal department and agency heads are responsible for the identification, prioritization, assessment, remediation, and protection of their respective internal critical infrastructure and key resources” [12] (Bush, 2003). HSPD 7 covered those federal facilities included within the broad definition of critical infrastructure.

Sternberg and Lee (2006) argued that federal emphasis on protecting other critical infrastructure—typically described as utility networks, transportation systems and key industrial sectors—was a homeland security focus that overlooked the importance of government facilities, which they define as “large and complex human-occupied structures.”

One year after the aircraft terrorist attacks on the World Trade Center, the Federal Emergency Management Agency (FEMA) produced the first of two documents intended to help building designers and occupants address the threat of terrorist attack. The first, *Integrating Manmade Hazards into Mitigation Planning* (Federal Emergency Management Agency, 2002a), provided guidance to state and local governments to reduce or eliminate life loss and property damage from manmade disasters. It categorized human-caused hazards as technological hazards or terrorism. According to the document,

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[11] Defined as “systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters” (See USA Patriot Act of 2001, 42 U.S.C. §5195 *et. seq.*).

[12] Defined as “means publicly or privately controlled resources essential to the minimal operations of the economy and government” (See Homeland Security Act of 2002, 6 U.S.C. §101 *et. seq.*).

technological hazards refer to incidents that arise from routine human activities, such as the manufacture, transportation, storage, and use of hazardous materials. Terrorism, on the other hand, is defined as intentional, criminal or malicious acts.

The second FEMA publication, *Reference Manual to Mitigate Potential Terrorist Attacks against Buildings* (Federal Emergency Management Agency, 2003) described building fire hazards as technological accidents addressed in existing building codes, industry standards, and FEMA guidelines. The document acknowledged that:

> mitigation factors include built-in fire detection and protection systems and fire-resistive construction techniques. Inadequate security can allow easy access to target, easy concealment of an incendiary devices, and undetected initiation of a fire. Non-compliance with fire and building codes as well as failure to maintain existing fire protection systems can substantially increase the effectiveness of a fire weapon. (2003, p. 40)

The document provided a "Building Vulnerability Assessment Checklist," developed by the U.S. Department of Veterans affairs that compiled the best practices for design and construction based on contemporary technology and scientific research. Where guidance was provided on fire safety vulnerabilities, all the recommended solutions were based on existing prescriptive regulations and standards.

B. GENERAL SERVICES ADMINISTRATION CONSTRUCTION REGULATIONS

The GSA is responsible for the construction and management of all federally owned public buildings outside the District of Columbia and off military reservations.[13] In 2010, the GSA's Public Building Service (PBS) reported it managed more than 8,600 leased and owned buildings with a gross floor area in excess of 351 million square feet (3.2609×10^7 m^2). Of this, the GSA was responsible for more than 175 million square feet (1.6258×10^7 m^2) in more than 1,500 buildings, with the balance leased from private

[13] See 40 U.S.C. §3101.

owners. The three primary types of facilities are federal office buildings, courthouses, and land ports of entry[14] (U.S. General Services Administration, 2010a, p. 2). Clearly, the federal government is a major user and occupant of real property.

According to the Commission on Engineering and Technical Systems (Commission on Engineering and Technical Systems, 1989) "Federal agencies are exempt from these state and local building codes (and from zoning laws as well), and are entirely responsible for all aspects of safety and health in their buildings" (p. 2). However, the Public Buildings Act of 1988[15] specified that any building constructed or altered by the GSA or any other federal agency should be in compliance—to the extent feasible as determined by the GSA administrator or in the case of national security needs—with the latest published edition of one of the nationally recognized model building codes (Legal Information Institute, 2011a).[16] Beginning in 1996, the GSA has published a series of mandatory design guides called "Facilities Standards for the Public Buildings Service (P100)" (U.S. General Services Administration, 2010a). Although not a building code in the typical context, the P100 establishes GSA requirements for public buildings in the general areas of sustainability, energy conservation, physical security, and health and safety.

In the area of fire protection and life safety, the P100 standard establishes a performance goal to:

> incorporate into all projects fire protection and life safety systems that are effective in detecting, extinguishing, or controlling a fire event, thereby improving overall building safety to an acceptable level.

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[14] See Appendix A for the legal definition of "public buildings."

[15] See 40 U.S.C. §3312.

[16] This legal mandate has been overtaken by events; in 1988, three nationally recognized model buildings codes existed. Today, the GSA P100 recognizes only one: the International Code Council's *International Building Code* with modifications to the means of egress requirements where the National Fire Protection Association's *NFPA 101 Life Safety Code* is required.

> The primary goal is to protect human life from fire and products of combustion. The secondary goals are to reduce Federal Government and taxpayers' potential losses from fire (i.e., protect Federal real and personal property, maintain client agency mission continuity, and control environmental impact). (2010a, p. 235)

Although the goals describe key elements, such as occupant safety and the need to maintain mission continuity, arson related fire threats are not mentioned. In fact, the word arson does not appear in the P100 standard.

The P100 standard requires that all projects have a licensed fire protection engineer on the architectural design team to conduct an overall building fire safety analysis, and specifically design features, such as the means of egress, fire protection water supply, and specialized fire protection systems. This private-sector fire protection engineer is authorized to propose deviations from the prescriptive P100 construction requirements, and these must be submitted for approval to the GSA regional fire protection engineer who has oversight authority on fire protection and life safety features of the project (U.S. General Services Administration, 2010a). Alternative designs may include a performance-based approach so long as the "proposed alternative is deemed equivalent of superior to the intent of the prescribed requirements" (p. 236) of the P100 standard. In addition to the general fire protection design requirements, P100 references other federal standards for special use occupancies. Table 3 summarizes these additional standards.

Table 3. Special Federal Fire Protection Design Guides based on Occupancy (After: U.S. General Services Administration, 2010a)

Occupancy	**Design Guide**
U.S. Courts	P 100, Chapter 9 and the *U.S. Courts Design Guide*
U.S. Marshal Service	*USMS Requirements and Specifications for Special Purpose and Support Space*, Volumes I, II, and III
Land Ports of Entry	*Land Port of Entry Design Guide*
GSA Child Care Centers	*GSA Child Care Center Design Guide* (PBS-140)

The 2010 edition of P100 includes references to *the ISC Physical Security Criteria for Federal Facilities* and adds special requirements if the ISC risk management process determines the project under consideration to have high protection risk level (see Figure 2). In those instances, P100 requires that the project design team conduct a fire protection risk assessment of the building. According to the P100 standard:

> the fire protection risk assessment is a technical evaluation, based on professional rationale and judgment, of potential risks involved in achieving desired objective(s) (e.g., protection of life, the property, and the mission). It involves the measurement and complete documentation of conditions and features relevant to determination and adjustment of the level of building safety and the adequacy of the protection provided. The overall combined effect of all positive features and negative conditions must be considered in the evaluation rather than the effects of a single item or concern. The result will be a logical and reliable determination of whether equivalent or alternative solutions exist for any or all negative conditions caused by an unwanted event. (U.S. General Services Administration, 2010a, p. 257)

C. PRESCRIPTIVE DESIGN AND CODES

Despite the long-standing application of prescriptive designs and codes, where the architect and building contractor are compelled to follow a prescribed set of materials and methods to satisfy safety requirements, no literature evaluates their effectiveness. Most of the research that exists is critical of prescriptive designs and codes in that they lack suitable safety objectives, stifle innovation, and needlessly increase the cost of building construction. Hadjisophocleous, Bénichou, and Tamin (1998) reported in their own literature review that although prescriptive codes proved easy to verify compliance with the regulations, their drawbacks included the following.

- Specific requirements were established with no clear objectives
- Cost-effective designs were not promoted
- Very little flexibility existed for innovation or unusual conditions
- A presumption that there was only a single design solution that provided a level of safety (which itself was not defined)
- Challenges applying them to large, complex buildings

In a follow-up article, Hadjisophocleous and Benichou (2000) reiterated their earlier findings that prescriptive codes "have the advantage that designers can do a design by just following prescriptions and that code officials can easily determine whether a design follows code requirements" (pp. 140–141), but the impediments to innovation, the limited application to complex designs, and the lack of clearly articulated safety objectives remained.

Oster and Quigley (1977) were critical that building codes acted as a deterrent to innovation in both building design and the use of new construction materials that could increase functionality and reduce costs. In 1981, the U.S. Department of Housing and Urban Development conducted a historical survey of the "Evolution of Building Regulations in the United States" (Building Technology, 1981). The report found that over time, building codes evolved to employ three primary technical requirements: 1) design requirements and criteria for building elements and systems for various occupancies, 2) specifications for construction materials, and 3) construction details. In all cases, these requirements were prescriptive in their nature.

A sample of building code officials, who generally were employees of local governments, and were charged with the interpretation, application, and enforcement of construction codes, were polled in 1996 to research their willingness to accept performance-based designs, which then were a relatively new concept in building construction. Van Rickley (1996) found that almost 80% of those polled agreed with the statement "prescriptive building and fire codes, as they currently are written, are necessary to ensure reasonable levels of fire protection and life safety" (p. 43). In a study assessing the potential economic opportunities for wood products in non-residential building construction, Goetzel and McKeever (1999) found that prescriptive building codes limited the structural size and height of buildings, especially where combustible construction was employed.

Lord and Marrion (2003) studied building codes in six developed nations and found that the prescriptive codes did not always provide the design flexibility or functional needs expressed by a developer or tenant, and provided only a limited set of

solutions. Siu (2005), in an evaluation of three historically significant high-rise office fires,[17] found that after each of the events, "the question has been raised whether prescriptive building codes provide adequate protection for the structure" (p. 1). Siu added that the economic and societal losses of the three buildings also proved that prescriptive building codes were not adequate to protect buildings from fires. Licht (2005) argued that technical changes that occurred during consolidation of the three national model prescriptive codes[18] into a single document resulted in an overall reduction in fire and life safety, and especially, put fire fighters at risk.

In projects not particularly complex or requiring unusual design features, prescriptive codes can satisfy basic design and occupancy needs. Occasionally, however, specific circumstances arise that do not fit within the strict confines of a prescriptive code. To address these conditions, the legacy and current model construction codes permit the designer to propose the use of alternate methods or materials, as long as the resulting construction is determined to be equivalent to the requirements of the prescriptive code. In these cases, mixing prescriptive requirements with performance-based designs may satisfy both the code official and the permit applicant. Mirkhah (1997b) found this approach to provide a desirable solution to a complex design problem for a unique high-rise entertainment structure in Las Vegas. Geren (2004) supported this approach as a means of providing modern building designs without sacrificing safety or quality.

[17] The fires occurred in the First Interstate Bank in Los Angeles, May 4, 1988, One Meridian Plaza in Philadelphia, February 23, 1991, and New York's World Trade Center Building 7 on September 11, 2001. The outcome of these fires and the buildings' performance has been studied extensively among fire protection professionals.

[18] The Building Officials and Code Administrators International *National Building Code*, the Southern Building Code Congress International *Southern Standard Building Code*, and the International Conference of Building Officials *Uniform Building Code* were consolidated in 2000 into the *International Building Code*.

D. PERFORMANCE-BASED DESIGN

Performance-based fire safe building design[19] is grounded in scientific and engineering principles used to solve fire protection and life safety challenges. Consequently, a substantial portion of the literature addresses results from empirical fire research and human behavior studies. Less contemporaneous writing on the policy implications of performance-based design is occurring, and a growing body of opinion on its merits is appearing. In Europe and Pacific Asia, where performance-based design has been established since the mid 1980s, the policy literature is richer. Also, a group of professionals are wary of performance-based fire safe building design, and argue that longstanding consensus-based prescriptive methods better serve fire safety needs because of their built-in redundancies that have accumulated from collective fire experiences. The modeling documentation often used in performance-based design is not yet developed enough to be reliable.

Performance-based fire safe design advocacy started in the United States in the mid-1960s. Watts, Jr. (1966) argued for a fire safety objectives approach in an editorial in *Fire Technology*, the quarterly scientific and engineering research journal published by the National Fire Protection Association. He suggested that scientists and engineers needed to move from vague statements to a precise and specific measure of performance.

In the United States, the seminal literature for performance-based design was a report prepared by the U.S. General Services Administration (GSA) in 1972 entitled *Building Fire Safety Criteria, Appendix D: Interim Guide for Goal–Oriented Systems Approach to Building Firesafety*.[20] The report was the result of a GSA conference in 1971, an International Conference on Fire Safety in High-Rise Buildings (Meacham, 1998c). The document provided a groundbreaking new approach to building design by "demonstrating that engineers can view the building and fire as integral components of a

[19] For simplification, the term performance-based design is used throughout this text as a general term that encompasses performance-based, objective-based, and functional design (Meacham, 1998a).

[20] In the fire protection field, spelling "fire safety" as a single word, "firesafety," is a commonly accepted practice.

single system, and that [the traditional method of] evaluating or designing individual components without regard to the system, potentially severe shortcomings in the design could result" (Meacham, 1998a, p. 4).

As a proof of concept that could be applied to a GSA project then under development, engineers borrowed an event logic diagram that became known as the fire safety concepts tree. The diagram was founded in the system safety analysis and fault tree analysis process developed by the National Aeronautics and Space Administration to enhance reliability in the nascent space program. This logic-based decision-making tool eventually became the National Fire Protection Association (NFPA) *NFPA 550, Guide to the Fire Safety Concepts Tree* (National Fire Protection Association, 1995). Starting with the goal of "prevent fire ignition," the fire safety concepts tree plotted fire safety design objectives through a series of "OR gates" that gave designers alternatives to choose one solution or another.

The U.S. Department of Commerce National Bureau of Standards followed the GSA interim guide in 1979[21] and the U.S. Department of Health, Education and Welfare study *A Theoretical Rationalization of a Goal-Oriented Systems Approach to Building Fire Safety* (Watts Jr., 1979). This report articulated the concepts of deterministic and probabilistic approaches to fire safe design as alternatives to traditional prescriptive compliance. The deterministic approach "presumes an ability to determine the precise behavior of any fire at any time in the future, given exact contemporary conditions and the antecedent state of the building and its contents" (Watts Jr., 1979, p. 7). At this time, Watts Jr. acknowledged not enough scientific data existed to employ this method.

On the other hand, the goal-oriented or probabilistic approach derived in the GSA Appendix D, reasoned that a certain amount of hazard was unavoidable and that "a fire safety goal, such as maintaining the continuity of an organizational mission, could be expressed in terms of a probability of limiting fire extent" (Watts Jr., 1979, p. 9).

[21] The National Bureau of Standards is now the National Institute of Science and Technology.

Beck (as cited in Meacham, 1998a) conducted research in Australia to develop a building fire safety model that estimated the level of risk for the particular building being modeled. The model was based on the probability of events occurring at a specific time related to the time of fire ignition. The model used five sub-systems (nature of occupancy, fire growth and development, smoke management, flame management, and occupant avoidance and fire fighting) to identify consequences in terms of the number of people exposed to dangerous conditions (Meacham, 1998a).

The next significant development in the literature was Fitzgerald's *Building Firesafety Evaluation Method* created in 1985 (as cited in Meacham, 1998a). Unlike the fire safety concepts tree, Fitzgerald's approach was to work inversely from a likely ignition scenario and, using network diagrams, evaluated factors, such as ignition potential, fire growth potential within, and from a compartment,[22] and occupant safety. Within the network, at any point, an experienced user could apply subjective probabilities—or statistical data—to estimate the likelihood of each event occurring with an anticipated outcome that was the likelihood of whether any event will or will not occur (Meacham, 1998a).

In the 1980s, a substantial portion of the literature focused on empirical fire and human behavior studies (see next section). During this time, several countries, including the United Kingdom (UK), Japan, Australia, and New Zealand, rewrote their national building regulations to de-emphasize prescriptive requirements, and encourage performance-based solutions.

By 1998, although much of the rest of the developed world embraced performance-based designs, in Assessment of the Technological Requirements for the Realization of Performance-Based Fire Safety Design in the United States—Phase 1: Fundamental Requirements, Meacham found that the United States was still reluctant to do so because of the lack of documentation and credibility of the state of engineering

[22] In the fire protection field, a compartment generally describes a space having boundaries of at least a floor, walls, and ceiling. The size, shape, slope, materials, and dimensions of each plane are immaterial at this level of definition.

tools and methodologies for fire safe building design (Meacham, 1998a). The Society of Fire Protection Engineers and National Fire Protection Association in 2000 took a major step toward resolving the documentation and protocol issues by publishing *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings.* This workbook provided a step-by-step method to identify and document the design parameters employed in performance-based projects (National Fire Protection Association & Society of Fire Protection Engineers, 2000).

In "Accommodating Perceptions of Risk in Performance-Based Building Fire Safety Code Development," Wolski, Dembsey, and Meacham (2000) introduced the two methods of adding risk factors to buildings, and categorized them as low, medium, or high risks. In the first method, risk adjustment factors could be adjusted during the deterministic analysis of the building design to assess if additional fire safety features would be needed. The second method would be applied during the probabilistic approach to develop risk conversion factors related to expected-risk-to-life values so design adjustments could be made dependent upon the perceived fire safety risk to occupants.

Bukowski (2006) provided a post-September 11, 2001 assessment in *Determining Design Fires for Design-Level and Extreme Events.* The jet fuel-fed fires that destroyed the World Trade Center north and south towers exceeded the commonly anticipated scale of performance-based designs for past and current high-rise office buildings.

More recently, a federal interagency working group consisting of representatives from DHS, Department of Justice, U.S. Nuclear Regulatory Commission, the GSA, and Administrative Office of the U.S. Courts, published a design standard entitled *Physical Security Criteria for Federal Facilities: An Interagency Security Committee Standard* (U.S. Department of Homeland Security, 2010c). The standard strongly emphasizes the importance of a facility security committee that identifies threats, vulnerabilities, and countermeasures as part of a risk-based decision process for design, which is a significant step toward a performance-based fire safe design in federal facilities.

When stakeholders and the design team establish a project's fire safety objectives, a critical point of agreement must occur regarding the nature of what are called design

fire scenarios. These scenarios generally include the range of fire challenges that could or likely would occur in a given building or facility based on the nature of its use, contents, and even threats. It is the variety of scripted fire scenarios against which the design team must show its proposed solutions will mitigate or control the event as a measure of success, which is one of the shortcomings of the *Physical Security Criteria for Federal Facilities: An Interagency Security Committee Standard.* Without a clearly articulated arson fire scenario, rational countermeasures to address the threat or reduce vulnerabilities cannot be developed and prescriptive solutions may not be satisfactory. Zalok and Hadjisophcleous (2009) found that "the development of a design fire scenario is a combination of hazard analysis and risk analysis. Hazard analysis identifies potential hazards, such as ignition sources, fuels, and fire development. Risk analysis includes the indicated hazard analysis and the likelihood of occurrence (either quantitatively or qualitatively), and the severity of the outcomes" (Zalok & Hadjisophocleous, 2009, p. 1082).

According to the SFPE (National Fire Protection Association & Society of Fire Protection Engineers, 2000), each scenario should define three components: fire characteristics, building characteristics, and occupant characteristics. Fire characteristics include the anticipated range of possible fire scenarios from an unintentional error to an arson attack. The potential rate of fire growth, its expected time to flashover, and when it may be extinguished, must be considered. Building characteristics include architectural features, such as large open spaces or small compartments, structural components and building materials, fire protection systems and equipment, building services (e.g., heating, air condition, elevators and escalators), and fire department response capabilities. Occupant characteristics include the potential number of occupants, their distribution through the building, alertness, mobility, and physical or psychological conditions.

As part of its P100 "Facilities Standards for the Public Buildings Service," the GSA adopted the national consensus standard NFPA 101, "Life Safety Code." The standard includes eight design fire scenarios that must be used if an architect or engineer elects to use a performance-based design approach in lieu of a prescriptive method. Table

16 summarizes the elements of the eight design scenarios. Yung and Benichou (2002) offered a sample of six different design fire scenarios based on the nature of the fire (smoldering, flaming or flashover) and whether the entrance door to the room in which the design fire occurred was open or closed. They also acknowledged that the prediction of fire growth in a room—before it happens—was difficult due to the almost limitless number of configurations of the type, quantity, and arrangement of combustible contents, as well as where those combustibles might be ignited:

> The proposed design fires depend only on parameters that can be characterized *a priori*,[23] such as occupancy type, amount of combustibles, size of the compartment, and the ventilation conditions. Random parameters, such as the arrangement of the combustibles and the point of ignition, are taken into consideration by using statistical information on probabilities of fire types. (Yung & Benichou, 2002, p. 232)

This statement on the need to evaluate random parameters is important in the assessment of protecting federal facilities. Although Yung and Benichou emphasized the need for statistical sampling on fire types, they did not mention significant statistical anomalies, such as the World Trade Center attacks of September 11, 2001. This shortcoming may be due to the fact their research was presented in 2000,[24] and published only two years later.

In a 2003 report commissioned by the National Science Foundation, (Lucht et al., 2003) found that current performance-based design and building practices offered “real promise for regulators and public officials to institute regulations that reflect a better understanding of risks and improved safety performance for buildings in their communities” (p. 3).

Thompson and Bank (2007) compared existing performance based design practices and standards for seismic protection and fire safety, and determined an opportunity does exist to use performance based design protocols for terrorism resistant buildings. They claimed the first step toward acceptance of this method would be the ability to characterize the types of terrorism-related hazards facing building designers and

[23] In this context, “before the event.”

[24] Yung and Benichou’s paper originally was presented at the 5th Fire Risk and Hazard Assessment Research Application Symposium in Atlantic City, New Jersey, June 28–30, 2000.

criteria for acceptable levels of risk. Thompson and Bank reported, “to be truly effective at improving the safety of building occupants, a methodology must address the full range of terrorism-related threats, including not only traditional blast attacks, but chemical and biological agent attacks, and attacks on any system in the building” (p. 66).

Bwalya (2009) reported that the choice of design fires must be influenced by the nature of the fire safety assessment or design tasks being undertaken. While the routine concerns about the type and nature of combustibles, ignition method, fire growth, and fire decay were important, “there is a requirement for the design fire to represent a fire that presents a formidable challenge to whichever fire safety feature or aspect of a building is being evaluated” (p. 181).

E. COMPUTERIZED FIRE MODELS AND VALIDITY

In developing and evaluating the safety objectives in performance-based designs, it is not feasible to build a full-size version of the building or facility under study and set it on fire to observe the outcome. Consequently, computerized fire effects models often are used to test hypotheses and assess the potential outcome of design fires. It is important to note that fire effects models are not predictive, but are representative of data collected from full- and small-scale fire tests and post-incident analysis of real world events. Can fire modeling results be considered valid for their applicability to building and facility design where human lives are at stake and property must be protected from a variety of threats? In the fire protection context, validity is a measure of the model’s ability to replicate real world fire events. Models continue to improve as they are compared to experimental (live) fires and data sets become richer in the scientific and research literature.

Fire effects models are divided into four major categories that simulate the fire environment: zone, field, large eddy simulation, and direct numerical simulation models (Gissi, 2010). All use complex mathematical formulas to quantify the physical characteristics of the fire environment. Zone models typically are one- or two-dimensional, and operate on the assumption that the space where the fire is being

modeled—generally called a compartment—is divided into two realms: an upper zone of hot fire products of a relatively uniform temperature and composition, and a cooler lower zone containing some amount of contaminants. Field models divide the compartment being studied into three-dimensional cells (the size of which can be adjusted) and the calculations describe the physical interaction between and among cells that thus enable a more detailed assessment of the fire environment. Zone models tend to be less sophisticated and require less computing capacity. Field models are more complex and require powerful computers.

Large eddy simulations attempt to capture accurate relationships between the turbulent mixing of gases and combustion products within the immediate area around the fire (Gissi, 2010). They require smaller computational grids and substantial computing power and speed. Direct numerical simulation performs complex equations without any discrete space or time considerations for turbulence, which means the entire fire environment is modeled simultaneously. According to Gissi (2010), direct numerical simulation is the most sophisticated means of fire simulation, and consequently, exceeds the capacity of the most powerful computers available today.

Other computer models employed in fire protection analysis include tools that simulate the response time of fire detection devices, such as heat detectors or automatic sprinklers, egress models that evaluate human movement in buildings to assess evacuation performance, fire endurance models to evaluate how various building components react to fire exposure, and models that address detailed topics, such as glass breakage, smoke movement, or flame spread.

Attempts to model complex fire behavior began in the late 1950s when Japanese researcher Kawagoe studied the relationships between temperature and ventilation on the outcome of room fires (Kawagoe, 1958). Subsequently, a number of researchers began to develop hand-calculated mathematical formulas to explain fire behavior that they studied. The expansion of the electronic computer in conjunction with the growing international study of fire behavior has made fire modeling a preferred tool in the evaluation of performance-based designs. By 1992, one survey of the contemporary state of fire

modeling found 74 models from 13 countries were then in use (Friedman, 1992). The understanding of fire behavior and the ability to replicate it in computerized fire models has progressed dramatically in the last 20 years.

Friedman (1992) found that models he surveyed might not compare to actual fire behavior for any of the five following reasons.

- Idealizations and simplifications on which the model was based might deviate significantly from real world conditions
- Input parameters (data entry) supplied to the model were inaccurate
- Defaults values of the coefficients in the underlying computational routines were flawed
- The computational process itself yielded incorrect results due to time and scaling problems in the mathematical equations
- The experiments themselves were not correct or could not be repeated

In 1996, Babrauskas reported that contemporary fire models were unable to reproduce even the most fundamental characteristics of fire behavior. Babrauskas's survey (1996) found that modeling software in use at the time was unable to reproduce flame spread, heat release rate, fire or smoke chemistry (especially the production of carbon monoxide), a realistic mixing of heated gas layers within a compartment, or the influence of fire suppression.

To provide professional design guidance, in 1997, ASTM International (ASTM)[25] published two documents: *Standard Guide for Determining the Uses and Limitations of Deterministic Fire Models* (ASTM E1895) and *Standard Guide for Evaluating the Predictive Capability of Fire Models* (ASTM E1355). The first provided guidance for users and code officials in establishing the appropriate uses and limitations of fire models in fire risk and hazard assessments (ASTM International, 2007). The second, ASTM E1355, provided methods for evaluating models by comparing their analytical precision to standard fire tests, full-scale fire experiments, field experience, published literature, or previously evaluated models (ASTM International, 2011).

[25] Formerly the American Society for Testing and Materials. It is a non-profit organization for developing, delivering, and coordinating voluntary consensus standards.

In 2002, 16 researchers from 10 countries conducted a round robin modeling exercise to compare their results from a single fire scenario. The purpose of the round robin was to determine if modelers could obtain similar results from the same inputs, and thereby, validate the models' reliability to portray real world events. The design fire consisted of a single room with a wooden material fire source. The participants used two field models and nine two-zone models in their assessments. After comparing fire model outputs to live experimental fires, Keski-Rahkonen and Hostikka (2002) found deviations between the modeled results and the live fire data, principally because the types of fires were not well suited for the zone models. They also found discrepancies in the results ranging from ± 10% up to a factor of two, which were in the same range of uncertainty as the experimental data. However, the differences were attributed not to the models, but to the skills of those performing the data input.

By 2003, Olenick and Carpenter found the number of fire models had grown to almost 140, and that computer modeling of fire and smoke transport was becoming a more accepted practice because of improvements both in knowledge about fire behavior and improved computer performance. Olenick and Carpenter (2003) reported that since Friedman's survey, "increased use of modeling is also attributable to the move towards performance-based building codes in the United States and other countries. Instead of using a prescriptive building code, engineers now can design for egress of building occupants under varying fire conditions" (Olenick & Carpenter, 2003, p. 88).

Salley et al. (2007) assessed the accuracy of fire model results and found that for some study areas, zone models were adequate (e.g., ceiling temperatures and flame heights), and the more sophisticated field models were better suited for some analysis (e.g., predicting heat flux and fire behavior in asymmetrical compartments). However, for complex fire scenarios, design engineers should employ field modeling because the results are likely to be more reliable.

Beard (2008) expressed apprehension that an inexperienced user may interpret the fact that a model has been validated means it somehow will accurately predict real world conditions. This perception is a legitimate concern of many fire protection professionals

who fear that an inexperienced or disingenuous modeler may use the technique inappropriately. According to Beard (2008), different users of a model may produce very different results based on inputs and variable controls. The next year, Beard cited the following potential error sources in modeling.

- Inputting data presented as a realistic depiction of real world events without acknowledging that the conceptual and numerical assumptions in a model were only an approximation of actual fire behavior
- Failing to follow the strict protocols for the model being used that potentially could result in both mathematical miscalculations and errors in scale
- Fundamental computational errors in the software. Beard claimed one estimate suggested as many as eight possible errors for each 1,000 lines of computer source code
- Faults in computer hardware that might be the result of a flawed micro-processor design, manufacture, or a combination of both
- Errors entering data or interpreting the results
- Inadequate documentation that implies the model selected is appropriate for the scenario being represented when it may not be the best available tool (Beard, 2009)

In their assessment of one of a series of highly instrumented and documented apartment fire tests in Dalmarnock, Scotland, Rein, Jahn, and Torero (2011) found that fire simulations conducted before the live fires (a priori) dramatically overpredicted temperatures of hot gas layers and surfaces by 20 to 800 percent. A posteriori modeling reduced the error range to 10–200 percent. They concluded the following.

- Even in a posteriori simulations (with full access to the measurements) it is not easy to reproduce the fire
- The incapability of predicting fire growth is shown to be a fundamental constraint to fire modelling [sic]
- When the HRR [hear release rate] is unknown as it is in most practical cases, the use of lower and upper HRR bounds should be included as to reflect in the predictions the effect of uncertainty in the HRR. This is an important issue for the application of fire modelling [sic] to real scenarios when the HRR us unknown (i.e., [sic], forensic investigation and assumed design scenarios). (p. 10)

Jahn, Rein, and Torero (2008) reported that fire-modeling tools provide good predictions of the thermal consequences of a fire, but their ability to predict fire development and HRR is problematic; therefore, it is incumbent on the modeler to specify the HRR input variable. In a recent study, Zalok and Hadjisophocleous (2009) attempted to create virtual fuel load configurations in seven different commercial-type buildings. The purpose was to develop data inputs based on fuel load surveys that could be inputted into a fire effects model,[26] and thereby, reduce the need to conduct detailed surveys or conduct full-scale fire tests. They found that "although models might not always give accurate predictions, the results of validated models can be used with confidence in the design of fire protection systems" (p. 20). Their research showed that the difference between predicted peak HRR and the experimental peak HRR was less than 16%, "giving confidence in the model for use in predicting more complicated cases" (2009, p. 20).

F. FIRE AND BEHAVIOR STUDIES

Empirical fire research and human behavior studies for performance-based fire safe building design are intended to quantify the interaction among fire ignition, product or material combustibility, fire and smoke behavior, building structural and fire resistance features, fire protection systems and human behavior, such as relocation, shelter-in-place, or evacuation. These studies have helped designers better understand the role of these elements in a single system. While these studies add substance to the engineering applications of performance-based designs, they are outside the scope of this thesis, which is focused on policy implications of performance-based fire safe building designs.

Titles, such as *Natural Smoke Filling in Atrium with Liquid Pool Fires Up to 1.6 MW* (Chow, Li, & Huo, 2001), *A Computational and Experimental Study of Fire Growth and Smoke Movement in Large Spaces* (Kashef, Bénichou, Lougheed, & Mccartney, 2002), *Experimental Fire Tower Studies of Elevator Pressurization Systems for Smoke Control* (Tamura & Klote, 1987), *Characterization of Fire Induced Flow Transport*

[26] In this study, they evaluated a field model, Fire Dynamics Simulator.

Along Ceilings Using salt-Water Modeling (Yao, 2006), and *A Performance Based Methodology Using Travelling Fires for Structural Analysis* (Spence, 2000), illustrate the scope and scale of empirical fire behavior studies. Many of the studies focused on a single fire behavior or the performance of a single building component when exposed to controlled fires in a laboratory.

Magnusson, Frantzich, and Harada (1996) in “Fire Safety Design Based on Calculations: Uncertainty Analysis and Safety Verification” described results from occupant evacuation studies conducted in a one-room public assembly building using a number of uncertainty analysis procedures including the analytical first-order second-moment (FOSM) method, two numerical random sampling procedures (simple random sampling and Latin hypercube sampling), and standard probabilistic risk analysis methods. Their work was just one of several that studied human behavior in fires that reviewed both reaction and response times to queuing and evacuation actions.

G. GLOBAL EXPERIENCE WITH PERFORMANCE-BASED DESIGN AND CODES

In Europe and Pacific Asia, performance-based fire safe designs have been employed for more than two decades. These designs have provided the designers and regulatory authorities an opportunity to assess the success or failure of this design option.

In Hong Kong, Walters, and Hastings (1998) studied 14 years of disastrous multiple-death fires in that colony, and found that in addition to cultural complacency, a weak and outdated regulatory environment correlated to the significant losses. They noted in Fire Safety Legislation in Hong Kong, for the latest fire codes of practice that are applicable to new work, “the Government has started to include performance-based criteria as an ‘alternative approach to fire engineering.’ The use of performance codes requires legislators and policy makers to be explicit in their objectives and standards of public welfare and safety” (p. 253). New Zealand has substantial experience with performance-based fire safe building design. Buchanan produced a small study from nine city councils around the country entitled “Implementation of Performance-Based Fire

Codes." The results showed survey participants believed the new codes resulted in a major increase in perceived safety for building occupants, but a significant decrease in property protection (Buchanan, 1999).

On the other hand, Buchanan, Deam, Fragiacomo, Gibson, and Morris (2006) found that performance-based design has increased architectural flexibility and reduced construction costs, but also resulted in some problems including different levels of enforcement across the country, and poor workmanship, especially where local building inspections have been insufficient to ensure the expected quality of design or on-site workmanship from the small number of poorly qualified designers or sloppy builders who cause problems. Buchanan et al. findings were corroborated by additional research in "Performance-Based Regulation and Regulatory Regimes: The Saga of Leaky Buildings" (May, 2003). Consequently, New Zealand has had to adopt stricter building code regulations. One study, *New Zealand Fire Service Design Review Audit*, identified poor submittal documentation as a problem for regulatory officials (I. Thomas, 2006). New Zealand recently modernized its fire safety approach in building codes with the creation of "Verification Method: Framework for Fire Safety Design" (New Zealand Ministry of Business, Innovation and Employment, 2012) that requires a chartered professional engineer to satisfy 10 design fire scenarios with detailed consideration given to six parameters: fire growth rate, peak heat release rate, fire load energy density, gas species production (carbon monoxide, carbon dioxide, water and soot), heat flux, and time. The new regulations are intended to require a greater level of detail in fire modeling data inputs to achieve a more robust analysis of the outputs.

Canadian researchers Hadjisophocleous and Benichou (1999) found that performance-based design strategies often were used to satisfy alternative material and method solutions for satisfying rigid prescriptive building code requirements. In South America, Tavares (2009) began studying Brazilian cultural acceptance of performance-based designs in his work "An Analysis of the Fire Safety Codes in Brazil: Is the Performance-Based Approach the Best Practice?"

Swedish authors, Cronsioe, Stromgren, Tonegran, and Bjelland (2012), reported that too much freedom in the application of performance-based design might increase the uncertainty in levels of fire safety. They advocate a more consistent transnational approach (especially in Europe) to identify appropriate fire safety objectives while accounting for differences among legal frameworks, practitioner skills, and code officials.

H. POLICY CONSIDERATIONS

The goal of performance-based design is to make architectural decisions on well-articulated scientific and engineering principles while encouraging design freedom, reducing costs, and minimizing construction redundancies that have evolved in the prescriptive methods. For years, owners, architects, and builders have been constrained by the obligation to "meet the code," often without a logical or contemporary nexus to fire behavior or occupant safety. The potential change from prescriptive to performance methods has policy impacts for the government and its constituents.

In the UK, Europe, and Pacific Asia, prescriptive building regulations that had been in place for many years have given way to performance-based solutions. In the UK for example, prescriptive building regulations that had evolved from the 1666 Fire of London had grown to more than 300 pages. The government initiated an effort to increase design flexibility—and "produce a more intelligent system"—by publishing its 23-page *Building Regulations* that still covered essential safety, health, and comfort standards (Meacham, 1998a, p. 13). Similarly, the Japanese rewrote their building standards law into *The Total Fire Safety Design System of Buildings* (Japan Ministry of Construction, as cited in Meacham, 1998a). In Australia, a Building Regulation Review Task Force developed the first draft of that country's performance-based code, the *National Building Fire Safety System Code* (Meacham, 1998a).

In the United States, the local or state jurisdictions must promulgate and enforce building and fire safety. Not only is this an authority vested in the states by the U.S. Constitution, but it has historical precedent as well. In the United States, individual states

and communities often developed their own building and fire safety codes. In an article on regulatory barriers to innovation and marketing residential properties, Oster and Quigley (1977) found “the bewildering variation in local regulations may very well mean that potentially profitable innovations are also illegal in many geographical areas. This reduces both the scale at which an innovation can be marketed and its profitability, and may further discourage R & D investment” (p. 363). They added, “Ideally, construction standards would be a codification of performance specifications for newly constructed dwellings” (p. 365).

In 1927, the West Coast Fire and Building Officials, later known as the International Conference of Building Officials, published the first “model”[27] prescriptive building code, the *Uniform Building Code* followed by the *Standard Building Code,* published by the Southern Building Code Congress International in 1946, and the Building Officials and Code Administrator’s *National Building Code* published in 1950 (Bukowski, 1997). All these documents established prescriptive design requirements, and generally were updated on a three-year cycle to meet changing technology and market conditions.

The three organizations competed for primacy with the building and related construction codes until 1994 when the groups merged to form the ICC that now publishes the prescriptive *International Building Code.* In 2001, the ICC published the first American performance-based code, the *ICC Performance Code for Buildings and Facilities.* Another organization, the National Fire Protection Association, publishes a competing building code containing performance-based elements, NFPA 5000, *Building Construction and Safety Code*. The National Fire Protection also produces NFPA 101, *Life Safety Code* that includes a variety of performance-based design solutions within its criteria.

In 1993, in *Status of Performance Fire Codes in the USA*, Snell summarized the current state of performance-based design acceptance within the United States. He found

[27] Model codes are intended to be sufficiently generic so that any community code can adopt them as published, which results in a comprehensive and legally defensible set of building regulations.

that while the potential benefits of design freedom and cost saving were admirable, the research, technological, and legal foundations for the method had not yet gained acceptance. He optimistically expressed that modern advances in computing, telecommunications, simulation, and expert systems would offer exciting mechanisms to solve many of the design and application challenges (Snell, 1993).

Meacham (1998b), a prolific author and advocate for performance-based fire safe building design, summarized the state of its acceptance in *Concepts of a performance-based building regulatory system for the United States.* The report provided input on why the United States was moving toward a performance-based design system, what components were needed to make it work, and what education and qualifications issues needed to be addressed among practitioners and regulatory officials.

Bukowski (1997) pointed out that a significant cultural shift among designers, engineers, and code enforcement officials will be needed to embrace the move to performance-based designs. This change will require: 1) better training and education, 2) consensus upon which analytical techniques and data are appropriate for assessing designs, and 3) recognition that performance based designs will rely on new fire protection system technology more than fire-resistive construction and materials.

In a legal context, Coglianese, Nash, and Olmstead (2004) reported that "expanding the use of performance-based regulation holds promise for achieving health, safety, and environmental goals at a lower cost and for doing so in a way that accommodates if not encourages technological innovation" (p. 723). In their *Performance-Based Regulation: Prospects and Limitations in Health, Safety and Environmental Protection*, they found the design and cost-savings advantages of performance-based regulation do not necessarily mean it is always the best regulatory strategy.

In "Risk-Informed Performance-Based Approached to Building Regulation," Meacham (2010) reported a growing worldwide interest in combining risk analysis and engineering data with stakeholder interests to establish meaningful performance levels and criteria. Meacham stated that "keys to success include providing thorough yet

transparent decision framework, adequate data and analysis tools, and good stakeholder communication" (p. 892) all of which should be readily available in the federal government decision-making environment.

I. ALTERNATE VIEWS

Some are circumspect about performance-based design. Most notably, attorney and University of Maryland School of Fire Protection Engineering professor Vincent Brannigan has written extensively in American journals and periodicals regarding his concern that although technical inputs can be provided in performance-based designs, the unpredictable "human factor" may obviate a successful fire outcome (Brannigan & Smidts, 1999). He also expressed concern that no public policy mandate exists to move from the traditional prescriptive methods of design and construction, and what constitutes a reasonable level of safety is ill-defined in the performance-based design vernacular (Brannigan, 2001b).

In 2002, Brannigan expressed additional concerns about performance-based designs that may not consider the full impact of events that threaten buildings.

> Arson is a special issue for performance-based design because of engineering design optimization, a well-known problem. Highly engineered structures have clear-cut design specifications, but if something isn't reflected in the requirements, the structure may not be able to handle the problem. The engineers who optimized the Titanic designed it to hit icebergs head on, not to scrape along the side. The engineers who designed airbags made them safe for the 5-foot-9-inch, 160-pound passenger, but fatal to shorter people. (Brannigan, 2002)

He was equally concerned that the recently developed ICC *Performance Code for Buildings and Facilities* was legally flawed as a regulatory statute because its overall social objective for fire safety was not clearly articulated in legal terms (Brannigan, 2001a). In 2002, Brannigan softened his position somewhat and encouraged the use of "proportionate response" cited in the *ICC Performance Code for Buildings and Facilities* where the design and response of the building is proportionate to the potential fire threat (Brannigan, 2002).

Babrauskas (n.d.) in “Performance-Based Building Codes: What Will Happen to the Levels of Safety?” argued that successful strategies for performance-based design can be implemented, but that designers and regulatory officials should proceed cautiously before accepting them as a wholesale solution to fire protection challenges.

> The final consideration is that to develop a workable, safe performance-based building code is a very difficult endeavor. Many of the prerequisites needed are simply not in place today. Thus, working towards the day when FSE-based [fire safety engineered] fire safety designs will flourish is a noble effort, but precipitous haste is not. The consequences of such haste are likely to be erection of buildings with serious fire safety shortcomings. (p. 7)

Snell (1993) cited opponents who argued that the adoption of performance-based designs would increase design complexity and cost. In Hong Kong, Lo, Lam, Yuen, and Fang (2003) found that building code officials there generally supported performance-based designs but were suspect of the state of the engineering studies and analytical tools used to justify the method.

Mirkah (1997a) reported a reluctance on the part of many code officials to accept performance-based design applications because of their lack of knowledge regarding both complex fire behavior and sophisticated computerized fire effects modeling techniques often used to demonstrate that a proposed fire protection design was satisfactory to provide an acceptable level of safety for occupants, fire fighters, and the structure. He added that many code officials believed they may be vulnerable personally to tort liability claims should the proposed design fail with resulting deaths, injuries, or damages if the project did not meet the articulated requirements of a prescriptive code. Finally, Mirkah found a general distrust of fire protection engineers who represented a permit applicant. According to Mirkah, code officials were suspect that the engineers may not have been entirely objective since the developer is paying them. Later, Siu (2005) made the same finding that code officials had not obtained a comfort level with fire protection engineers because the discipline was relatively new compared to architecture or other engineering fields.

Finally, while Lucht et al. (2003) support the policy and cost benefits of performance-based design, they acknowledge that “significant gaps in the data and knowledge base needed to support performance-based codes, engineering tools, predictive models, and risk assessment” remain (p. 3).

J. LITERATURE GAPS

Although rich and diverse sources of literature on building construction, fire protection, performance-based designs, fire and human behavior research, computerized fire modeling, federal facilities, and terrorist threats do exist, significant gaps remain in the literature that combines this topic into a single framework.

First, because they do not include measurable objectives, prescriptive designs and codes have not been subjected to critical post-incident analysis to evaluate if they performed as the persons involved in the consensus-based development process expected they would. Many articles and legal cases assess the performance of individual building components or sub-systems, or assign liability where failures occurred, but no overall evaluation of whether the deemed-to-satisfy approach created a safe building environment. Building and fire code changes that occur over time often are the consensus response to significant tragedy.

Likewise, no literature assesses the post-incident performance of buildings or facilities constructed with performance-based designs; thus, it is impossible to determine if the initial design objectives were met. As time passes and buildings that employed performance-based designs suffer fires, an opportunity exists to evaluate the results. Given well-developed criteria, the chance to compare performance-based and prescriptive designs also exists to determine if one is preferable to the other.

Considering the number, size, and value of federal government real property assets, comprehensive studies of fire and/or arson incidents and their impact on both physical property and continuity of operations are in order. It is remarkable the GSA, the government’s largest non-military property manager, has no meaningful instrument to collect and analyze fire and/or arson incidents, especially since it has been more than 10

years since the GAO identified this shortcoming. The existing method of collecting incident information is archaic and does not allow for detailed analysis so the GSA can make informed planning and construction decisions. No body of literature enables government policy makers to make rational, performance-based decisions on fire protection.

The literature on fire modeling and design fires lacks empirical evidence on the impact of potential arson fire scenarios, including the use of large quantities of flammable liquids, multiple fire starts, and the effects of compromised fire protection systems or fire resistive construction. Most fire modeling is predicated on a single ignition point in a normalized (non-criminal) environment.

Combined, these gaps show that no consensus method exists to develop threat scenarios against which architects or engineers can design so-called permanent countermeasures. This study will add to the literature by evaluating one of the 31 design threats developed by the ISC to suggest that quantified threat scenarios improve the decisions employed for the *Physical Security Criteria for Federal Facilities* standard.

III. FEDERAL FACILITY SAFETY SINCE 1995

The means of protecting federal facilities from a variety of terrorist threats has evolved since a 1995 attack in Oklahoma City that killed 168 civilians, including 19 children. Since then, the federal government has promulgated a variety of physical security standards intended to protect occupants, visitors, facilities, and equipment in existing and new buildings while increasing the government's ability to be resilient in the face of attack. Most of these standards were based on prescriptive design methods, while more recent efforts have begun to implement performance-based characteristics. This section reviews the recent developmental history of these federal standards.

A. *VULNERABILITY ASSESSMENT OF FEDERAL FACILITIES* (1995)

On April 19, 1995, Timothy McVeigh perpetrated a dramatic and deadly act of domestic terrorism when he bombed the Alfred P. Murrah federal building. The next day, President William J. Clinton ordered the U.S. Department of Justice (DOJ) to conduct a short-term study assessing the vulnerability of federal office buildings to terrorism and other acts of violence. Seven federal agencies participated in the study,[28] and two working groups (a Standards Committee and Profile Committee)[29] were created to meet the President's ambitious 60-day deadline. The survey focused on the GSA-controlled single or multi-tenant office buildings. By October 1995, DOJ issued the 91-page *Vulnerability Assessment of Federal Facilities* (hereafter *Vulnerability Assessment*) report that established six strategic security recommendations and created 52 recommended minimum-security standards for federal facilities. The recommendations were applicable to existing buildings, but did not include standards for new construction.

[28] The DOJ (including the U.S. Marshals Service [that served as the lead agency] and Federal Bureau of Investigation), the GSA, the Department of Defense, the Secret Service, the Department of State, the Social Security Administration, and the Administrative Office of the U.S. Courts.

[29] The Standards Committee developed minimum-security standards. The Profile Committee was tasked to survey sample federal facilities to determine existing security features, and identify future security enhancements and costs.

The strategic recommendations included: 1) bringing federal facilities up to minimum security levels concomitant with their assumed vulnerability, 2) establishing building security committees, 3) reemphasizing GSA's primary responsibility for implementing federal facility security, 4) creating an ISC, 5) upgrading the FPS, and, 6) using tenant rents to cover the cost of security improvements. Elements of recommendations 1–4 are addressed within this study; upgrading the FPS and evaluating recovery costs are not.

The study teams determined that of the one million federal civilian employees, about 50% worked in GSA-owned or controlled space. Almost 75% worked in what GSA called a "typical single or multi-tenant federal office building" (U.S. Department of Justice, 1995), and the DOJ report estimated 1,330 of these facilities existed in the continental United States.[30] The typical federal building generally was a multi-story building housing more than 80 employees, containing a mix of federal agencies, most of which had significant needs to interact unimpeded with the public. The remaining federal employees worked in facilities not included in the survey sample, including special use space, such as laboratories, national parks, nuclear facilities, military installations, or post offices (U.S. Department of Justice, 1995).

According to the report, "prior to the study, there were no government-wide standards for security at federal facilities, and no central data base of the security currently in place at such facilities" (U.S. Department of Justice, 1995). This seminal effort focused on perimeter,[31] entry, and interior security, and security planning, which created a scale of five increasingly restrictive security levels. Although criminal and terrorist acts as a class were addressed, the term "security" was not defined in the initial report, nor has it been defined in subsequent reports.

Table 4 describes the five recommended security levels and includes examples cited by the survey teams. The criteria are very prescriptive (e.g., number of employees

[30] During the 60-day survey, site visits were made to 1,239 locations (U.S. Department of Justice, 1995).

[31] The report concluded perimeter security (parking, closed circuit television monitoring (CCTV), lighting, and physical barriers were areas outside the government's control.

and building area) without any rational justification for the selected values. No justification exists that a building housing 149 federal employees qualifies as Security Level II, but one with just two more employees should increase to Security Level III, which is an example of prescriptive standards based on non-scientific, subjective decisions.

Table 4. Building Security Levels: 1995 Vulnerability Assessment (After: U.S. Department of Justice, 1995, pp. 2-3–2-5)

Security Level	**Criteria**
I	A building that has 10 or fewer federal employees; low volume of public contact or contact with only a small segment of the population; and 2,500 or less square feet (232 m^2) of space, such as a small "store front" type of operation.
II	A building that has 11 to 150 federal employees; moderate volume of public contact; 2,500 to 80,000 ft^2 (232 to 7 432 m^2) of space; and federal activities that are routine in nature, similar to commercial activities. A typical Level II building is the Social Security Administration Office in El Dorado, Colorado.
III	A building with 151 to 450 federal employees; moderate/high volume of public contact; 80,000 to 150,000 ft^2 (7 432 to 13 935 m^2) of space; and tenant agencies that may include law enforcement agencies, court/related agencies and functions, and government records and archives. A typical Level III building is the Pension Building, a multi-tenant, historical building on 5th Street Northwest, in Washington, D.C.
IV	A building that has 451 or more federal employees; high volume of public contact; more than 150,000 ft^2 (13 935 m^2) of space; and tenant agencies that may include high-risk law enforcement and intelligence agencies, courts, and judicial offices, child care center and highly sensitive government records. A typical Level IV building is the Department of Justice Building on Constitution Avenue in Washington, D.C., and the Alfred P. Murrah Building would have been assigned this category.
V	A building that contains mission functions critical to national security, such as the Pentagon or CIA Headquarters. A Level-V building should be similar to a Level-IV building in terms of number of employees and square footage. It should have at least the security features of a Level-IV building. The missions of Level-V buildings require that tenant agencies secure the site according to their own requirements.

Noticeably absent was any reference to arson as a potential threat because the 1995 report's contemporaneous emphasis was on mass explosive devices, which makes sense given the nature of McVeigh's attack mode, and the criteria and deadline under which the study group was working to satisfy the President's order. Two references related to fire protection occur in the report. First, as listed in Table 5, the survey teams found approximately 76.9% of the facilities they visited were outfitted with complete fire detection/suppression systems. However, the data's validity is of concern. One problem with this data is that the survey instrument used does not discriminate between fire detection and fire suppression[32] systems so it is impossible to deduce from the data the number of facilities protect by fire detection, fire suppression, or both types of systems. Secondly, the modifier "complete" is not explained; therefore, it is impossible to determine the actual extent of protection these systems provide.

Table 5. Surveyed Facilities: Fire Protection Features (After: U.S. Department of Justice, 1995, p. E-32)

Protection Level	**Facilities**	**Estimated Percent**
Complete fire detection/suppression system covering all areas of the facility	910	76.9
Fire detection/suppression system covers a portion of the facility	196	16.6
No fire detection/suppression system present	77	6.5
Total	1,183[a]	100.0

[a]The survey reported 1,239 site visits were conducted. No explanation was given for the data discrepancy.

A second fire reference in the *Vulnerability Assessment* report occurs in its Appendix B, "Details of Recommended Security Standards," under the category of access control with

[32] In this application, fire detection refers to electronic systems for detecting heat, smoke, or other combustion products, and subsequently, reporting an alarm. A fire suppression system generally implies automatic sprinkler systems that are heat-activated and discharge water.

the recommendation to "upgrade to current life safety standards: required for all facilities as part of GSA design requirements (e.g., fire detection, fire suppression systems, etc.)" (U.S. Department of Justice, 1995).

One of the report's recommendations was that all facilities have a formal mechanism for addressing security issues, and the responsibility for fulfillment should lie with a GSA-mandated and controlled Building Security Committee (BSC). The BSC[33] would include representation from all agencies occupying the building, and the GSA would designate a physical security specialist[34] to assist the committee. The BSC was expected to evaluate and apply appropriate minimum requirements that needed to be implemented at its facility, as well as identify other building-specific security issues (U.S. Department of Justice, 1995).

Furthermore, the 1995 report stressed the important role the GSA played in implementing federal facility security. By law,[35] only the Administrator of General Services may construct a non-military or non-postal public building, and is authorized to alter it by delegating that responsibility to GSA employees and agents, but the *Vulnerability Assessment* applied only to existing buildings. The *Vulnerability Assessment* recommended that the GSA should review all the BSC security enhancement requests, evaluate how approved requests should be amortized into tenant rents, and amend the GSA facility construction master planning process to assure that only functionally similar agencies are housed in the same location so agencies with dissimilar missions (e.g., law enforcement and environmental protection) are not co-located in the same facility (U.S. Department of Justice, 1995).

The *Vulnerability Assessment* concluded that "the typical federal facility at each security level lacks some of the elements required to meet the new minimum standards

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[33] The BSC designation eventually morphed into Facility Security Committee (FSC) in the *Physical Security Criteria for Federal Facilities* April 12, 2010 standard (p. 12).

[34] Physical security specialists develop security policy and design, develop, evaluate, and sometimes install protection systems and devices to insure that sensitive information, equipment, and other material is not compromised, sabotaged, stolen, misused, or subjected to terrorist, malicious mischief, or other acts of willful interference (U.S. Office of Personnel Management, 1987).

[35] See 40 U.S.C. § 3302 (2010) and 40 U.S.C. § 581 (2010).

proposed in this Study" (U.S. Department of Justice, 1995) and recommended that, where feasible, each federal facility should be brought up to the minimum standards proposed for its corresponding security level. The study included seven reasons for the current (1995) security levels.

- GSA's prior security levels, like most agencies before the Murrah Building bombing, were directed at a different kind of threat—protecting federal workers and visitors from theft or assault—than significant terrorist attacks.
- Prior to the study, no government-wide standards existed for security at federal facilities, and no central database of security is currently in place at such facilities against which any standards could be measured.
- Violent or terrorist threats had not been "an overriding factor in building design" (U.S. Department of Justice, 1995). Tight security was considered inimical to easy citizen access for high service levels.
- Agencies with differing security needs often shared facility space leading to inconsistent application of security measures.
- FPS security services were based on a periodic risk assessment process.
- The typical local organizational structure was insufficient to meet tenant security needs, especially where multi-tenant facilities existed. No formal relationship existed between FPS and the tenants for conflict resolution.
- Facility security efforts were sometimes fragmented, with different agencies assigned to perform different functions within the same facility (U.S. Department of Justice, 1995).

The report recommended that because each federal building was unique—and the feasibility of upgrading existing conditions was dependent upon building-specific facts—security issues should be addressed at the building-level security committee, with follow-up analysis performed by the GSA.

Most significant to this thesis, the 1995 *Vulnerability Assessment* report recommended the creation by Executive Order (EO) of an ISC to do the following.

- Establish policies for building security, including, but not limited to, those recommended in the study
- Develop a strategy for ensuring compliance with approved standards
- Oversee the implementation of appropriate security measures in federal buildings

In addition, the ISC would encourage interagency cooperation on security issues, assess technology as a means of providing cost-effective security enhancements, assist in budgeting oversight to prioritize federal security needs, develop long-term construction standards for these locations with threat levels or missions that require blast-resistant structures, evaluate standards for the location of—and special security related to—day care centers in federal facilities,[36] and assist the GSA in developing and maintaining a centralized security database (U.S. Department of Justice, 1995). The *Vulnerability Assessment* report remained in effect until it was superseded by the April 12, 2010 issuance of the *Physical Security Criteria for Federal Facilities*, discussed later in this section.

By 1998, Peck, in testimony before the Subcommittee on Public Buildings and Economic Development of the House Committee on Transportation and Infrastructure, reported that 90% of the estimated 8,000 identified security upgrades in 8,300 GSA controlled buildings had been made, and 75% of the recommended countermeasures had been completed (Peck, 1998). However, a 1998 report from the General Accounting Office was critical of the GSA's progress on meeting its performance goals, and that the security improvements program had at least three significant flaws.

> GSA has not established several key program evaluation mechanisms for its building security program that could assist it in determining how effective its security program has been in reducing or mitigating building security risks or in shaping new security program initiatives. These features are (1) specific goals, outcomes, and performance indicators for the security program, such as reducing the number of thefts or unauthorized entries; (2) establishing and implementing systematic security program evaluations that would provide feedback on how well the security program is achieving its objectives and contributing to GSA's strategic goals; and (3) ensuring that a reliable performance data information system is place. (Ungar, 1998)

[36] Following the deaths of 19 children under the age of six in the Alfred P. Murrah Building bombing, the sensitive nature of childcare centers located in federal facilities required additional special attention. Any facility with a childcare center automatically received a facility population score of "very high."

Ungar's testimony introduced the concept of performance-based methods for building security. Terms, such as "specific goals, outcomes, and performance indicators," and "achieving objectives," move from the prescriptive approach to developing design solutions that can produce measurable results. Ungar further suggested that revisions in the building risk assessment methods—and simultaneous resumption of the FPS's periodic risk assessments—would provide a means to analyze the effectiveness of the adopted security measures and whether they would continue to be appropriate for future threats that may arise (Ungar, 1998).

B. CREATION OF THE INTERAGENCY SECURITY COMMITTEE (1995)

On October 19, 1995, President Clinton issued Executive Order EO12977, which established a permanent ISC within the executive branch to address continuing government-wide security for federal facilities (Smith, 2007). In language nearly identical to that recommended in the *Vulnerability Assessment* report, the ISC was chartered to establish policies for security and protection of federal facilities, develop and evaluate security standards for federal facilities, develop a strategy for ensuring compliance with such standards, and oversee the implementation of appropriate security measures in federal facilities. The ISC was authorized to do the following.

- Encourage agencies with security responsibilities to share security-related intelligence in a timely and cooperative manner
- Assess technology and information systems as a means of providing cost-effective improvements to security in federal facilities
- Develop long-term construction standards for those locations with threat levels or missions that require blast resistant structures or other specialized security requirements
- Evaluate standards for the location of, and special security related to, day care centers in federal facilities
- Assist the General Services Administrator in developing and maintaining a centralized security database of all federal facilities (Clinton, 1995)

Table 6 identifies the member agencies and representatives of the original ISC chaired by the GSA director.

Table 6. Original ISC Representation (After: "Executive Order 12977," 1995)

Department of Justice	Department of the Treasury
Department of Commerce	Department of the Interior
Department of Housing and Urban Development	Department of Labor
Environmental Protection Agency	Department of Transportation
Office of Management and Budget	Department of Veterans Affairs
Department of Agriculture	Department of State
Department of Health and Human Services	Department of Education
Director, United States Marshals Service	Department of Defense
Director, Security Policy Board	Central Intelligence Agency
Assistant to the President: National Security Affairs	Department of Energy
Assistant Commissioner of the Federal Protective Service of the Public Buildings Service	GSA

The ISC created four working groups to distribute work and accomplish its charter. Table 7 summarizes the assignments each committee was given within the ISC's overall framework.

Table 7. ISC Working Groups (After: Holt, 2010)

Working Group	**Assignment**
Steering Subcommittee	Provided overall project guidance, established priorities, recommended specific projects and initiatives.
Standards Subcommittee	Coordinated development and review of all ISC physical security standards.
Technology Best Practices Subcommittee	Identified best practices in security technology and provided guidance on cost-effective use of new technology to supplement and reinforce other security measures.
Convergence Subcommittee	Provided subject-matter expertise on best practices in providing agencies with mechanisms to support security programs, while integrating information management controls through a collaborative effort.

C. *GSA SECURITY CRITERIA* (1997)

In January 1997, the GSA completed its first draft of a document entitled *GSA Security Criteria*, which was revised and issued on October 8, 1997, to establish design standards for the protection of federal employees in new, significantly renovated, and long-term leased civilian facilities (U.S. General Services Administration, 1997). Nationally critical Level V facilities, defined in Table 3, were outside the scope of the new standard. The GSA document attempted to integrate security requirements throughout all functional and design phases of the building process, including site and interior space planning, as well as structural and electrical design elements (Smith, 2007).

While sensitive to the earlier DOJ criteria of Building Security Levels, the GSA approach included a mix of other categories beyond building size and population, which introduced value-laden criteria, such as symbolism, mission criticality, consequences of attacks, and threat vulnerabilities. Table 8 summarizes the categories and criteria.

Table 8. Categories and Criteria (From: U.S. General Services Administration, 1997)

Category	**Criteria**
Symbolic	Any thing or place for which a popular recognition exists of an object, name, or governmental activity by virtue of its historic significance, its size, its uniqueness, or its context with specific ideas or sets of values or attitudes.
Mission criticality	Degree to which a building houses operations and functions critical to national interests of the United States.
Consequence	Impact of an attack on a facility, including injuries and the loss of life; damage to the property or assets; interruption of the work done at the facility; and the time needed to repair, replace, or bypass the building to continue the work.
High consequences	Manifested effects of a criminal or criminal-like event that would involve the loss of life or the causation of injuries at to-be-defined levels. May also be the loss of, or damages to, tangible or intangible assets or the loss of irreplaceable assets and resources, all of which have significant worth on a national scale, and not limited to monetary considerations.

Category	Criteria
Threat	Terrorist threats, including bombs, chemical attacks, and biological attacks, or crime threats, based on local crime indexes.
Verified threat	Threat information authenticated by an official intelligence or law enforcement agency based on highly trusted sources or methods, and included information that a specific location or agency will be attacked within a contemporary time frame.

Abandoning the DOJ *Vulnerability Assessment* Levels I through V, the GSA created its own alphabetical list of four protection levels intended to be combined with threat and risk analyses to provide an assessment framework to measure the extent and cost of security features based on potential criminal or terrorist threats. Table 9 summarizes the GSA protection levels. Table 10 describes the crime or threat levels determined to exist where the facility would be constructed.

Table 9. GSA Protection Levels: 1997 (After: U.S. General Services Administration, 1997)

Protection Level	Application
D	When a building element[a] or building needs a high level of protection that would tend to be used when a building is a national symbol or of critical importance; and when its damage or loss will have high consequences, and when a verified high threat exists.
C	When a building element or building needs a medium-to-high level of protection that would tend to be used when a building is a regional symbol or has a significant impact on the government's mission, and when its damage or loss will have high consequences; and when a verified threat exists.
B	When a building element or building needs a medium-to-low level of protection. This level would tend to be used when the building is a regional symbol or has an impact on the government's mission, and when its damage or loss will have moderate consequences; and when a suspected threat exists.
A	When the building element or building does not need higher protection. This level would tend to be used when the building is of low consequence and when an unknown threat exists.

[a]Building elements includes foundations, structural framing, exterior and interior walls, roofs, and internal systems, such as heating, ventilation, air conditioning, electrical, plumbing, and fire protection systems.

Table 10. Protection Level and Crime/Terrorist Threat Levels (After: U.S. General Services Administration, 1997)

Protection Level	Crime/Terrorist Threat Levels
D	When a high local crime index exists,[37] when the building houses critical operations, or when it has high asset value.
C	When a medium local crime index exists, when the building houses sensitive operations, or when it has moderate asset value.
B	When a low local crime index exists, when the building houses routine operations, or when it has low asset value.
A	When the facility is small and has a very low local crime index, when the building houses routine operations, and when it has very low asset value.
N/A	Not applicable.

Using the characteristics described in Tables 8 and 9, design professionals could develop a matrix of protection levels for the various elements that comprise the construction, sub-systems,[38] and security operations of a federal facility. The first step in the analysis was to conduct a security assessment categorizing the facility for criminal and terrorist threats using guidance from the two tables. Then, a panel of security, blast, intelligence, and technical experts were expected to review the results to "ensure the application of appropriate and cost-effective security measures, and give the design team building-specific security criteria to work with" (U.S. General Services Administration, 1997, p. 5). The resulting matrix allowed that a facility might have different performance categories applied to each of its building systems so the highest threat level across any row of cells dictated the minimum protection level for the building element.

[37] Index crimes are the eight crimes the FBI combines to produce its annual crime index. These offenses include willful homicide, forcible rape, robbery, burglary, aggravated assault, larceny over $50, motor vehicle theft, and arson (Federal Bureau of Investigation, 2002).

[38] Including mechanical, electrical, plumbing, conveyance, heating, ventilation, air conditioning, and fire protection systems.

Figure 1 is a matrix of the results for a hypothetical building where intelligence and security analysts provide guidance from Table 10 that the specific building is identified as being in a neighborhood with a very low local crime index (Protection Level A). However, evidence exists of a limited bomb threat (Protection Level B), a verified biological threat of moderate consequence (Protection Level C), and a verified chemical threat of high consequence (Protection Level D). The left vertical axis labeled "Building Element" includes some of the components that comprises the construction and operation of a building. While not clearly articulated in the descriptors, fire protection features, such as fire resistant construction, or automatic fire suppression systems, typically could appear in one or more of the categories, such as building façade and interior walls (as fire resistant construction), and mechanical systems, electrical systems, and security systems (as fire detection or suppression systems). The category security operations is neither clearly defined nor explained in the report. From the text, it appears to include human elements, such as guard and employee training, operations plans, and emergency plans, and therefore, is not included in this analysis of the built environment.

In this hypothetical example, the threats to the first three items (mechanical systems, windows, and security systems), range left-to-right from low to high (A to D),[39] and since the high consequence threat from chemical attack is rated D, the protection level for those particular building elements must meet Level D, a so-called "high level of protection" (from Table 9) but still does not specify how the elements should perform when subject to an attack. For comparison, the highest level of protection for stand-off distance, building façades, interior walls, or electrical systems only reaches Protection Level B.

[39] The protection of mechanical systems is not applicable to criminal threats in this assessment method.

Building Element	**Threats**				**System Protection Level**
	Crime	**Bomb**	**Biological**	**Chemical**	
Mechanical systems	N/A[a]	B	C	D	D
Windows	A	B	C	D	D
Security systems	A	B	C	D	D
Stand-off distance	A	B	N/A	N/A	B
Building façade	A	B	N/A	N/A	B
Interior walls	N/A	B	N/A	N/A	B
Electrical systems	A	B	N/A	N/A	B
Security operations	A	B	C	D	D

[a]Not applicable.

Figure 1. Hypothetical Federal Facility Protection Level Assessment (After: U.S. General Services Administration, 1997)

Once the system protection level was established, designers were expected to find "corresponding protective measures in the engineering criteria" included in the *GSA Security Criteria*[40] document (U.S. General Services Administration, 1997). However, the engineering criteria were vague, and generally included prescriptive requirements. For example, the reference to protecting fire protection water supplies provides unjustified prescriptive dimensions from high threat areas,

> The fire protection water system should be protected from single point failure in case of a blast. The incoming line should be encased or buried, or located 50' away from high threat areas such as loading docks, front entrances, and parking, and the interior mains should be looped and sectionalized. (U.S. General Services Administration, 1997, p. 66)

40 In deference to the political and emotional sensitivity of childcare centers after the Murrah Building bombing, the report included these prescriptive requirements: "Child care centers may be located anywhere in low risk buildings. In medium to high-risk buildings and courthouses, they should not be within 100 feet from the main public entrance or a loading dock. They should also be placed 100 feet away from public parking unless there are compensating blast design measures" (U.S. General Services Administration, 1997, pp. 7–8).

The design intent of a performance-based engineered approach is clear; protect the system from a single point failure in case of a blast. However, the size and nature of the potential blast and its distance from the fire protection water system is not specified; therefore, it is impossible for a designer to develop performance criteria to comply with this requirement. Conversely, the arbitrary prescriptive requirement to encase, bury, or locate the supply 50 feet (15 m) from one or more parts of a building cannot be justified without a combined analysis of the site, soil conditions, building configuration, or threat.

D. *ISC SECURITY DESIGN CRITERIA FOR NEW FEDERAL OFFICE BUILDINGS AND MAJOR MODERNIZATION PROJECTS* (2001)

The GSA and the U.S. Department of State convened a symposium in November 1999 to discuss the "apparently conflicting objectives of providing security from terrorist attack while designing public buildings in an open society" (Knoop et al., 2001). The GSA and State rejected the idea that rigid, prescriptive design approaches provided the solution to the security/openness paradox and "challenged the design and security professions to find aesthetically appealing architectural solutions that achieve both security and physical protection; a balanced, *performance-based approach to security* [emphasis added] and openness" (Knoop et al., 2001, p. 2). With this challenge, the GSA and State opened the door to the performance-based design approach in federal facilities where security issues were concerned.

In May 2001, the ISC issued new guidance, the *Security Design Criteria for New Federal Office Buildings and Major Modernization Projects (ISC Security Criteria)*, based on the five security levels for federal facilities developed in the 1995 *Vulnerability Assessment* report. It did not include the more subjective criteria described in the *GSA Security Criteria* (1997) (see Tables 8 and 9).

According to Smith (2007), new ISC security requirements for construction projects strongly emphasized protection from explosives used in terrorist attacks. The new ISC requirements included the use of glazing protection to enhance blast-resistance for windows, the establishment of distances that buildings should be set back from the

street (called set-back or stand-off distances), vehicular access control to buildings, and the placement of air handling intakes to prevent the introduction of airborne contaminants. Two draft documents, one that addressed entry security technology, and the second, which pertained to preparedness for nuclear, biological, and chemical attacks, were not issued officially by the ISC membership (Smith, 2007).

The Office of the Chief Architect of the Public Buildings Service (an office within the GSA) asked the National Research Council (NRC) to establish a panel of design and construction experts to evaluate the criteria to determine if they "might be too prescriptive to allow a design professional 'reasonable flexibility' in achieving desired security and physical protection objectives" (Knoop et al., 2001, p. 2). The resulting Committee to Review the Security Design Criteria of the ISC comprised representatives from the disciplines of architecture, structural and fire protection engineering, blast-effects mitigation, physical security, and risk analysis and management.

The Committee to Review the Security Design Criteria (Review Committee) was critical of the 2001 *ISC Security Criteria*.

> The document in general appears to be a mix of performance objectives, prescriptive requirements, and references to industry standard designs. The committee believes that although full implementation of all the ISC criteria will provide some protection for building occupants against most blast-resistant threats and should significantly reduce injuries, the organization of the document makes it difficult to identify clearly the connections between the specific criteria and the performance objectives they are meant to achieve. It is also difficult to identify clearly how some criteria apply to specific components of building design. Because this is a critical element on a performance-based design process, the committee believes that rectifying this shortcoming should be given priority. (Knoop et al., 2001, p. 2)

Using the ICC's 2001 edition of the *International Performance Code for Buildings and Facilities* as a model, the Review Committee outlined how a performance-based design approach could be used to achieve the desired security and safety concerns while maintaining open access to employees and the public. The Review Committee also pointed out, however, "the document is also focused on the terrorist vehicle bomb as the

primary means of attack; there is little guidance on defending federal buildings and their occupants from chemical, biological, or radiological weapons" (Knoop et al., 2001, p. 41). Likewise, arson or fire threats were relegated to the category of naturally occurring hazards and were mentioned rarely. Without addressing these and other threats, the Review Committee reported, the outcome could result in "building performance not being considered comprehensively—for instance, failure to design for survivability of fire protection systems after a bomb attack could result in an otherwise avoidable post-attack fire" (Knoop et al., 2001, p. 41).

While encouraging greater reliance on performance-based design to meet a variety of security challenges, the Review Committee acknowledged a role for prescriptive design and improvements in design guidance remained.

> The continued use of both prescriptive and performance criteria is appropriate for several reasons, including the fact that in much of the building design process using prescriptive criteria need not limit creative design. Performance analysis and design are only needed for certain portions of the process, for example, the design of glazing to satisfy a unique threat or location. Structured appropriately, prescriptive criteria can be a means of meeting performance objectives. However, the ISC Security Criteria do not provide guidance on the amount and completeness of information to be provided in documenting a performance-based security design. (Knoop et al., 2001, p. 42)

The Review Committee issued a set of 13 short- and long-term recommendations to improve the implementation of the *ISC Security Criteria* while simultaneously enhancing security. One included encouraging the ISC and its member agencies to begin a comprehensive and timely review of the *ISC Security Criteria* to include the "creation of risk assessment and management tools as well as policy guidance for physical protection and security to guide the development of risk reduction strategies and a performance-based design process" (Knoop et al., 2001, p. 46).

E. *BUILDING SECURITY: ISC HAS HAD LIMITED SUCCESS IN FULFILLING ITS RESPONSIBILITIES* (U.S. GENERAL ACCOUNTING OFFICE, 2002)

Meanwhile, the GSA conducted an independent review of the ISC, and reported the interagency group had made little progress on some of its assigned responsibilities. While acknowledging the ISC had developed and issued security design criteria and minimum standards for building access procedures, and served as a forum for its working groups to discuss security related issues:

> it had made little or no progress in other elements of its responsibilities, such as developing and establishing policies for security in and protection of federal facilities, developing a strategy for ensuring compliance with security standards, overseeing the implementation of appropriate security in federal facilities and developing a centralized security database of all federal facilities. (U.S. General Accounting Office, 2002)

The GAO report reemphasized the NRC Review Committee's findings that the ISC lacks "performance goals and measures" (U.S. General Accounting Office, 2002, p. 16). The GAO blamed the shortcomings on a lack of consistent and aggressive leadership in the General Services Administration, inadequate staff support and funding for the ISC, and ISC's own difficulty in making decisions. The GAO acknowledged the GSA was taking steps to correct the problems. Since the GAO report was produced at the time Congress was considering creation of the DHS, the GAO recommended that the Director of the Office of Management and Budget[41] work with the DHS, the GSA and other entities to address the report's recommendations with whichever agency assumed responsibility for protecting federal facilities. Additionally, the GAO report suggested that during its deliberations, Congress considers clarifying the proposed DHS's jurisdiction on security-specific matters for federal facilities among the agencies that eventually would become DHS components.

[41] At the time, the Office of Management and Budget was both represented on the ISC and responsible for heading the government's efforts to establish the DHS (U.S. General Accounting Office, 2002).

After the passage of the Homeland Security Act[42] and the eventual creation of the DHS, the chairmanship of the ISC was transferred from the GSA Administrator to the Secretary of the DHS and a GSA representative was added to the ISC's membership. Within the DHS, the ISC chairmanship subsequently was delegated to the director of the FPS (Smith, 2007).

F. *ISC SECURITY STANDARDS FOR LEASED SPACE* (2004)

Following the issuance of the 1995 *Vulnerability Assessment*, some agencies reported that the standards guidance was not suitable for most locations that the federal government leased, and the result was an apparent double standard for facilities leased or owned. The DHS reported that:

> providing the level of security control, access control, guard service, magnetometers, garage control, setbacks, etc. recommended by the DOJ study and attainable in a federally owned location, is not easily attainable in the typical 10,000 square-foot lease [929 m^2]. (U.S. Department of Homeland Security, 2004, p. 3)

In response to these concerns, the ISC created a Lease Security Subcommittee to develop a separate set of standards for leased properties. The standards relied on four of the five security levels[43] recommended in the 1995 assessment, but were modified for the needs of leased spaces where real property improvements were under the control of the property owner, not the tenant. Major structural changes, façade reconstruction, interior improvements, and blast protection were limited; however, all Level II through IV leased spaces were required to install shatter-resistant material on exterior windows to reduce the threat of flying shards resulting from a perimeter explosion. The security standards for leased space were issued September 29, 2004. Meanwhile, an updated version of 2001 *Security Design Criteria for New Federal Office Buildings and Major Modernization Projects* was approved by the ISC membership the same day.

[42] Public Law 107-296, 116 Stat. 745, enacted November 25, 2002.

[43] While the 1995 *Vulnerability Assessment* included five levels, the highest (Level V) was applicable only to highly secured facilities with a national security mission, which was not likely found in a leased commercial space.

G. *HOMELAND SECURITY: FURTHER ACTIONS NEEDED TO COORDINATE FEDERAL AGENCIES' FACILITY PROTECTION EFFORTS AND PROMOTE KEY PRACTICES* (U.S. GOVERNMENT ACCOUNTABILITY OFFICE, 2004)

In 2004, the GAO produced an analysis of ISC performance to date for the U.S. House of Representatives Committee on Government Reform. The report indicated while the ISC had made progress in federal facility protection efforts, it still fell short in several key areas including planning, the development of goals and objectives, and coordination among federal agencies required to meet ISC standards (U.S. Government Accountability Office, 2004).

The GAO report, *Homeland Security: Further Actions Needed to Coordinate Federal Agencies' Facility Protection Efforts and Promote Key Practices*, identified six key practices that together could enable federal agencies to obtain a more comprehensive approach to physical security. Table 11 summarizes the six key practices and the descriptions provided in the GAO study.

Table 11. Key Practices in Facility Protection (After: U.S. Government Accountability Office, 2004)

Key Practice	Description
Allocating resources using risk management	Identify threats, assess vulnerabilities, and determine critical assets to protect and use information on these and other elements to allocate resources as conditions change.
Leveraging technology	Leverage technologies to enhance facility security through methods like access control, detection and surveillance systems.
Information sharing and coordination	Establish means of coordinating and sharing security and threat information with other government entities and the private sector.
Performance measurement and testing	Use metrics to assure accountability for achieving program goals and improve security at facilities.

Key Practice	Description
Aligning assets to mission	Align assets to mission and relocate staff to reduce vulnerabilities, to the extent agencies have excess and/or underutilized facilities.
Strategic management of human capital	Strategically manage human capital to maximize government performance and assure accountability in facility protection.

The GAO found during the course of its study a number of federal agencies had begun using one or more of the key practices in assessing and improving their facility protection, but systemic problems still existed including "developing quality data that form the basis for risk management, ensuring that technology will perform as expected, and determining how to measure the true impact that various approaches have on improving protection" (U.S. Government Accountability Office, 2004, p. 5). This conclusion emphasized the value of performance-based methods in facility security design because it allowed designers and tenants to address articulated risks and select from a variety of engineered solutions to improve protection. Two of the key practices identified in Table 11 are directly related to the precepts of performance-based design, allocating resources using risk management, and performance management and testing using metrics to assure accountability in design outcomes.

Regarding the application of risk management principles to facility security, the GAO report commented that in general while they can "take on various forms, our past work showed that most risk management approaches generally involve identifying potential threats, assessing vulnerabilities, identifying the assets that are most critical to protect in terms of mission and significance, and evaluating mitigation alternatives for their likely effect on risk and their cost" (U.S. Government Accountability Office, 2004). This comment captures the key characteristics of performance-based design, identify one or more problems, and develop design solutions to address them.

The GAO in 2006 published another report generally critical of the fact no government-wide guidance nor standard existed that agencies could use to measure the performance of their facility protection efforts (U.S. Government Accountability Office,

2006). The Government Performance and Results Act of 1993 (GPRA) required program performance measurements in federal agencies.[44] The GAO studied public- and private-sector entities in the United States, Australia, Canada and the UK to determine how they developed physical security performance measures. In response, the ISC implemented its own set of performance measures for security improvements with the 2009 publication of the *Interagency Security Committee Use of Physical Security Performance Measures.*

While the focus of the document was on the effective use of financial resources primarily to satisfy the GPRA, the report did contextually acknowledge the value of performance-based approaches as part of an overall security strategy.

> Without effective performance measurement data, the GAO said decision makers may not have sufficient information to evaluate whether their investments have improved security, reduced Federal facilities' vulnerability, and reduced the level of risk to an acceptable level. (U.S. Department of Homeland Security, 2009)

The conclusion that resources cannot be managed properly without effective performance measures is equally important to the physical security design professional. When objective measures regarding the performance of security countermeasures are provided, the design professional can develop realistic solutions that address the specific threat.

H. *FACILITY SECURITY LEVEL (FSL) DETERMINATIONS FOR FEDERAL FACILITIES* (2008)

In 2006, the ISC elected to update the building security level criteria published in the 1995 vulnerability study and remained unchanged in the subsequent years. An Existing Facilities Security Standards Working Group was established to review and update the standards in light of newly identified threats, such as those posed in the September 11, 2001, aircraft attacks on the World Trade Center and the Pentagon where fires subsequent to the aircraft impact resulted in substantial deaths, injuries, and damage. The working group developed a 16-page standard, published in 2008, that defined the

[44] Public Law No. 103-62, 107 Stat. 285, enacted August 3, 1993.

criteria and process a BSC should use to determine its facility security level based on mission criticality, facility symbolism, population, size, and perceived threat to tenant agencies. The standard was built upon the five security levels identified in the 1995 vulnerability assessment (Table 4) and modified subjective criteria borrowed, in part, from the 1997 GSA *Security Level Criteria* (Table 8).

Table 12 summarizes the latest ISC security level criteria modified from the DOJ and GSA models. While the categories mission criticality, symbolism, and threat remain similar to the 1997 GSA *Security Level Criteria*, consequence, high consequences, and verified threat were deleted. Facility population and facility size (borrowed from the DOJ 1995 vulnerability assessment) were substituted, and a new category "intangible factors" was added.

Table 12. ISC FSL Criteria (After: U.S. Department of Homeland Security 2008)

Category	**Criteria**
Mission criticality	Facility mission, particularly as it may relate to national essential functions[45] and other important business of the government.
Symbolism	External appearances or well-known/publicized operations within the facility that indicate it is a federal facility, and the potential negative psychological impact of an undesirable event occurring at a prominent federal facility.
Facility population	Peak total number of personnel in government space, including employees, onsite contract employees, and regular visitors.
Facility size	Square footage of all federally occupied space in the facility, including cases in which an agency with real property authority controls some other amount of space in the facility.
Tenant agency threat	Nature of public contact required in or resulting from the conduct of business is adversarial, or whether a history of adversarial acts committed at the facility, against facility tenants, or against the tenant agencies elsewhere existed.

[45] National essential functions are "that subset of essential functions that are necessary to lead and sustain the Nation during a catastrophic emergency, and that, therefore, must be supported through the Continuity of Operations (COOP) and the Continuity of Government (COG) capabilities" (U.S. Department of Homeland Security, 2008, p. 2).

Category	Criteria
Intangible factors	Reduced value of the facility and a corresponding reduction in the consequences of its loss, including potential for cascading effects or downstream impacts on interdependent infrastructure, or costs associated with the reconstitution of the facility.

The *Facility Security Level Determinations for Federal Facilities—An Interagency Security Committee Standard* retained some of the criteria from the 1995 vulnerability assessment. Federal properties be assessed periodically[46] and be assigned a FSL ranging from I (low risk) to IV (very high). Some facilities, because of mission criticality, uniqueness or symbolism, might warrant a special FSL V designation (U.S. Department of Homeland Security, 2008; U.S. Department of Homeland Security, 2010c).

Figure 2 represents the FSL determination matrix included in the revised standard. Using the matrix, points are assigned by the BSC based on its assessment of the factors that "make the facility a target for adversarial acts (threats), as well as those that characterize the value or criticality of the facility (consequences)" (U.S. Department of Homeland Security, 2008; U.S. Department of Homeland Security, 2010c). The sum of the assigned points established the preliminary FSL designation (Table 13); however, the FSL could be adjusted one level by the BSC's assessment of the "intangible factors." The "intangible factors" and any adjustments to the facility level score had to be justified by the BSC.

[46] According to the standard, security assessments for Level I and II facilities were to occur every five years, and every three years for Level III, IV and V facilities (U.S. Department of Homeland Security, 2008; U.S. Department of Homeland Security, 2010c).

Points					
Factor	**1**	**2**	**3**	**4**	**Score**
Mission criticality	Low	Medium	High	Very High	
Symbolism	Low	Medium	High	Very High	
Facility Population	<100	101–250	251–750	>750	
Facility size	<10,000 ft^2	10,001–100,000 ft^2	100,001–250,000 ft^2	>250,000 ft^2	
	< 929 m^2	929–9 290 m^2	9 290–23 226 m^2	> 23 226 m^2	
Threat to Tenant Agencies	Low	Medium	High	Very High	
					Sum of Above
Facility Security Level	**I** 5–7 points	**II** 8–12 points	**III** 13–17 points	**IV** 18–20 points	Preliminary FSL
Intangible adjustment	Justification				+/-1 FSL
					Final FSL

Figure 2. ISC FSL Determination Matrix (After: U.S. Department of Homeland Security, 2008)

Table 13. Point Value-Derived FSL (After: U.S. Department of Homeland Security, 2008)

Total Points	Facility Security Level
5–7	I
8–12	II
13–17	III
18–20	IV

The *Facility Security Level Determinations for Federal Facilities—An Interagency Security Committee Standard* made no recommendations regarding physical security construction, threat mitigation, or countermeasures. The BSC was required to either accept the risk it identified, or fund security measures to reduce the risk (U.S. Department of Homeland Security, 2008; U.S. Department of Homeland Security, 2010c).

Not surprisingly, given the broad and mostly subjective latitude with which BSCs could evaluate their facilities, Smith found “the successful integration of the federal government’s facility protection standards is a formidable challenge because it involves diverse agencies with varying perspectives on security issues” (Smith, 2007). A performance-based approach to security issues would enable these diverse agencies to identify their unique security challenges and address them with customized solutions.

I. *PHYSICAL SECURITY CRITERIA FOR FEDERAL FACILITIES* (2010)

On April 12, 2010, the ISC released the complementary documents the *Physical Security Criteria for Federal Facilities* standard and the DBT report.[47] Both were subject to a 24-month validation period before they were finalized. In accordance with the recommendations from the 2004 GAO report,[48] the *Physical Security Criteria for Federal Facilities* standard adopted a risk management approach to aid in identifying threats, assessing vulnerabilities, determining critical assets needing protection, adjusting resources as threat conditions changed, and, key to this study, selecting countermeasures to address threats and vulnerabilities. Using a 13-step decision point flowchart model (Figure 3) and several tables of anticipated threats and security design options, the *Physical Security Criteria for Federal Facilities* describes a process that officials can use to determine the security measures needed at a federal facility (U.S. Department of Homeland Security, 2010c). The new document replaces the 1995 *Vulnerability Assessment*, the *ISC Security Standards for Leased Space*, and the *ISC Security Design Criteria for New Federal Office Buildings and Major Modernization Projects*, which consolidated them into a single document. The standard is applicable to “existing buildings, new construction, or major modernizations; facilities owned, to be purchased, or leased; stand-alone facilities, Federal campuses, and where appropriate; individual

[47] The DBT subsequently was updated November 30, 2010.

[48] Homeland Security: Further Actions Needed to Coordinate Federal Agencies’ Facility Protection Efforts and Promote Key Practices.

facilities on Federal campuses; and special-use facilities”[49] (U.S. Department of Homeland Security, 2010c, p. 4).

Application of the new standard is predicated on the FSL designation utilizing the assessment methods found in the 2008 standard (Figure 2). Once a security assessment is conducted by the agency or component responsible for physical security at the site, the FSC assigns the building or facility a baseline level of protection (LOP) score, which is “the degree of security provided by a particular countermeasure or set of counter measures” (U.S. Department of Homeland Security, 2010c, p. 7). The FSL (ranked I–IV) becomes the foundation for decision making using the ISC Risk Management Process identified in Figure 3. This formalized risk management process provides the FSC a series of decision points where the committee may evaluate its security features to balance the LOP against the perceived risk.

It is important to understand the word “risk” and its use in the *Physical Security Criteria for Federal Facilities’* narrative. According to the document, risk is a “measure of the potential harm from an undesirable event that encompasses threat, vulnerability, and consequence” (p. 7). In this context, it implies that harm will occur and can be quantified. This perspective is similar Purdy’s findings (2010) that “it has been common for risk to be regarded solely as a negative that organizations should try to avoid or transfer to others” (p. 882). The International Organization for Standardization (ISO) has developed a consensus definition of risk ideally suited to both the *Physical Security Criteria for Federal Facilities* and the application of performance-based design to minimize the consequences of unwanted events. In the new ISO definition, risk is the “effect of uncertainty on objectives” (p. 882). In this context, no negative connotation exists, only that the anticipated results might be altered by outside influences; therefore, risk may be positive or negative.

[49] Example of special use facilities “include but are not limited to, high-security laboratories, hospitals, aircraft and spacecraft hangers , or unique storage facilities designed specifically for such things as chemicals and explosives” (U.S. Department of Homeland Security, 2010c, p. 14). By the nature of their use and contents, these facilities tend to be a high fire risk or an arson target.

In the ISC model, once the FSL is assigned and the baseline LOP established, the risk management process requires an identification and assessment of threats to the facility (Step 2). To aid the security organization's assessment process, a threat list of 29 euphemistically named "undesirable events" was included in the original document intended to provide a "conceptual scenario for use in identifying applicable countermeasures when applying this Standard" (U.S. Department of Homeland Security, 2010c, p. 72).[50] The security analysis is required to assess all the undesirable events on the list. Event scenarios ranged from ballistic attacks using a variety of weapons to robbery, theft, and unauthorized surreptitious entry to the premises. One postulated arson scenario is "an attack against a Government facility by knowingly and willingly setting a fire with intent to cause damage or destruction to the facility and/or physical injury or loss of life to the occupants" (U.S. Department of Homeland Security, 2010c, p. 72).

[50] A later version of the DBT increases this list to 31.

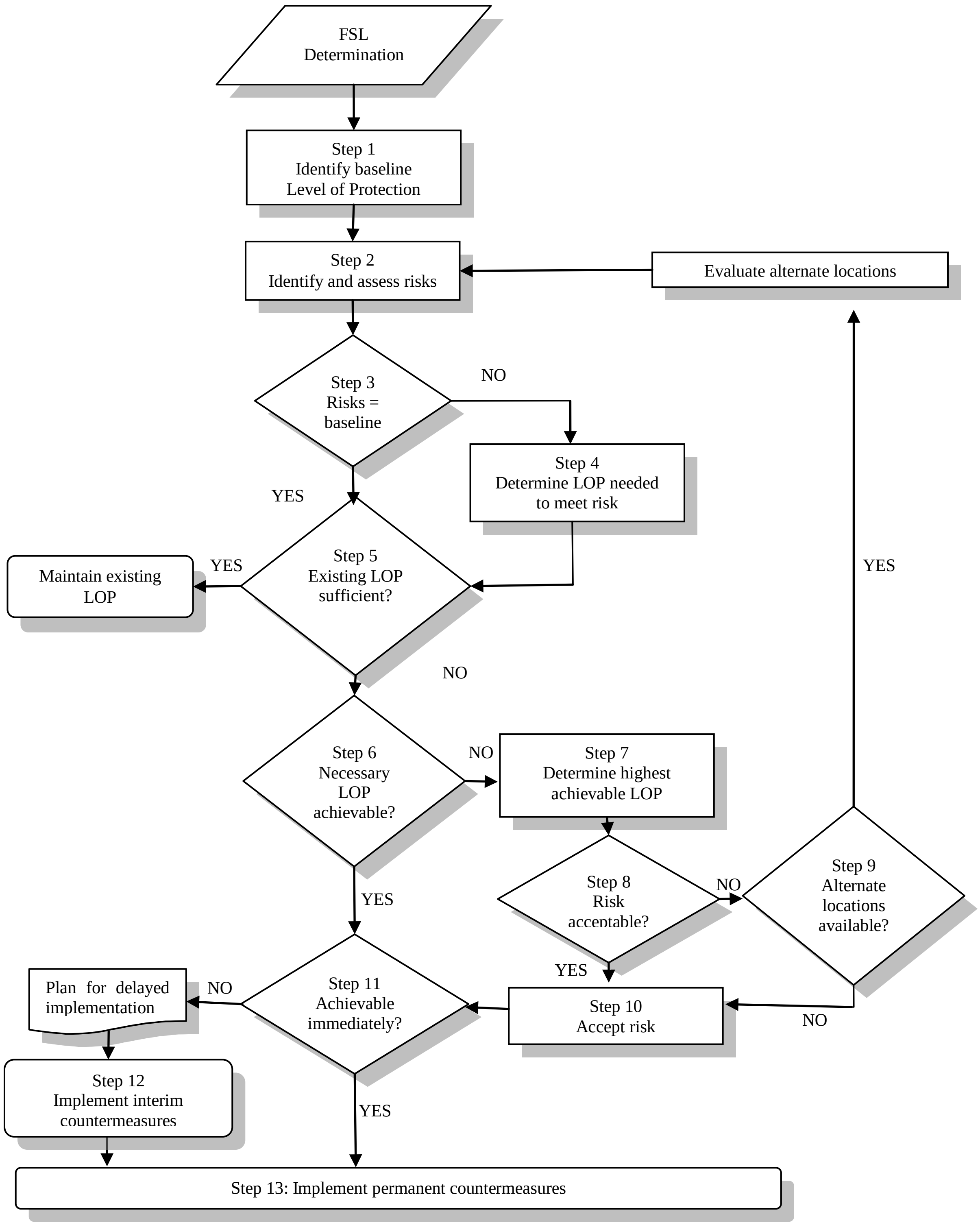

Figure 3. ISC Risk Management Process (After: U.S. Department of Homeland Security, 2010c)

Step 3 in Figure 3, the ISC Risk Management Process, is the first decision point, the FSC determination whether the baseline LOP adequately addresses the risks or if the LOP should be adjusted. If the FSC determines the baseline level of protection is sufficient, the existing protection levels are deemed adequate and no further security protections are required (Step 5). However, if the FSC determines the existing LOP is insufficient based on the risks, the committee must determine at Step 6 if the necessary LOP is achievable: "specifically, if the countermeasure can be physically implemented, and whether the investment is cost effective"[51] (U.S. Department of Homeland Security, 2010c, p. 27). If the FSC determines the necessary level of LOP[52] is not achievable, it must establish the highest achievable level of protection (Step 7). Once the highest LOP is determined, the FSC must decide if it needs to find alternate locations for the facility and its operations (Steps 8 and 9) or is willing to accept the risk (Step 10).

If, at Step 6, the FSC determines the necessary level of protection, or, at Step 10, accepts the existing risk, the committee is required to determine if the required countermeasures are immediately achievable or if interim countermeasures are required. Finally, at Step 13, the building or facility is required to implement the permanent countermeasures needed to satisfy the level of protection concomitant with the facility security level. While the term "permanent countermeasures" is not defined within the standard, an appendix of security measures is included that serves to address the various threats identified during the security assessment. Arranged in tabular format, the security criteria are a mix of vaguely defined prescriptive and performance-based countermeasures to the identified threats. Table 14 provides an example of how the security criteria are qualified that uses four security criteria generally applicable to fire protection and arson mitigation.

[51] Cost effectiveness is measured by comparing the cost of the countermeasure improvement to the value of the asset.

[52] Necessary LOP is defined as "the degree of security determined to be needed to mitigate the assessed risks at the facility" (U.S. Department of Homeland Security, 2010c, p. 7).

Table 14. Sample ISC Security Measure Details (After: U.S. Department of Homeland Security, 2010c)

Security Criterion	Detail
Hazardous Materials Storage	Comply with applicable regulations regarding storage and safety requirements. Depending upon the nature of the material, measures may be needed to prevent access to, release of, or unauthorized removal of the hazardous material from the site. Valves and control mechanisms also must be protected from unauthorized access.
Protection of Water Supply	Reference the current DBT established by the ISC, unless chemical, biological or radiation threat type is superseded by an agency-specific threat assessment.
Emergency Exit Doors	Electronic locks on perimeter doors must fail-secure, and electronic locks on interior doors must fail-safe, if such measures do not conflict with applicable fire and safety codes.
Security of Ventilation Equipment and Controls	To assure heating, ventilation and air conditioning system operation cannot be disrupted by someone physically accessing the controls; equipment should be located in a secure area with access limited to security and engineering staff.

Since many of the security criteria are vaguely defined, and simply are instructions selected from an established menu, no means is available to evaluate their effectiveness against an anticipated threat. For example, in the Table 13 security criterion for hazardous materials storage, the guidance to "comply with the applicable regulations regarding storage and safety requirements" provides only a directive and no measure of a successful outcome. On the other hand, the directive that "valves and control mechanisms also must be protected from unauthorized access" defines the desired security end state. The FSC or security organization can establish means to achieve this clear performance objective.

A second shortcoming of the *Physical Security Criteria for Federal Facilities* approach is its emphasis on threats that primarily are manmade. According to the report, "other threats to buildings, such as earthquakes, fire, or storms are beyond the scope of

this document and are addressed in *applicable construction standards* [emphasis added], although many of the countermeasures identified will contribute to mitigating natural hazards" (U.S. Department of Homeland Security, 2010c). This approach presumes the applicable construction standards—the model building codes—are adequate to protect against these and other natural hazards. The model building codes prescribe only minimum requirements, and do not have measurable outcomes of success. To say a federal building or facility "meets the code" is no assurance it will survive a natural threat since the scale and scope of the threat is not quantified in these construction standards. In other words, no performance expectation exists in the model construction standards, especially from threats, such as fire or arson.

J. *THE DBT* (2010)

Simultaneous to the release of the *Physical Security Criteria for Federal Facilities* standard, the ISC published a companion document, the DBT, which includes 31 scenarios potential adversaries might employ to attack federal facilities. The DBT was inspired by a similar, but classified, document used by the Department of Energy (DOE) to manage potential risks (U.S. Government Accountability Office, 2004). The scenarios expand on the undesirable events enumerated in the *Physical Security Criteria for Federal Facilities* and included intelligence community assessments of the likelihood one or more of the scenarios will be implemented by an adversary. As the ISC developed threat scenarios, it was guided by the importance of creating specific examples for which permanent countermeasures could be developed. However, the companion documents fall short of this objective in several ways. The scenarios are inconsistently defined, and some significant (albeit not criminal) threats are dismissed as outside the scope of the work.

According to the report, the intent of the DBT was threefold.

- To inform the deliberations of the ISC working groups as they establish standards
- To support the calculation of risk upon threat, vulnerability and consequences, to a facility, when applying the *Physical Security Criteria for Federal Facilities*
- To determine the specific adversary characteristics that performance standards and countermeasures are designed to overcome (U.S. Department of Homeland Security, 2010a)

It is the last bullet that this thesis addresses with the hypothesis that the described arson-specific adversary and threat characteristics are too vague to enable the development of effective performance standards and countermeasures to control the arson threat and consequences.

In developing the DBT, the ISC was challenged by the changing nature of criminal and terrorist threats, and recognized that a more flexible approach was needed to develop design standards and countermeasures. According to the DBT:

> First, the threat was typically based on publicized historical events, leading the government to design tomorrow's facilities to meet yesterday's threats. Today's dynamic threat environment suggests a need to react to rapid change. The elapsed time between the identification of a need for a new Federal facility and the time it is occupied can be as long as 7 to 10 years. In that time, the threat has likely changed substantially. Previous standards also incorporated aspects of the threat as part of the document itself, which made it difficult to keep the threat current without updating the entire standard. The threat changes faster than working groups can develop new standards. (U.S. Department of Homeland Security, 2010a, p. 1)

Furthermore, the committee recognized that a "one size-fits all" approach to physical security design was not appropriate for all federal facilities depending upon variables, such as the community in which the facility was located, neighborhood conditions, mission and operational functions, topography, and threats. The complexity of these variables—especially threats—led to the conclusion that prior, more generic methods of physical security assessments were not working. According to the report:

> the validity of the threat is routinely called into question, not only in the characteristics of the threat itself (e.g., device size, weapon caliber, sophistication of the adversary), but in its applicability to a specific facility. More information was needed to support the evaluation of the threat as it pertains to the estimation of risk for each facility. By providing guidance in that area, the consistency of threat ratings from facility to facility is improved. (U.S. Department of Homeland Security, 2010a, p. 1)

In numerous references throughout the DBT document, the ISC emphasized the importance of “specific,” “consistent,” and “detailed” threat scenarios that should be used for countermeasure selection and design. At one point, the committee reported:

> with multiple working groups developing and updating a variety of related standards, the need for consistent information regarding the threat to serve as the basis for all new standards is paramount. Each working group should be considering the same threat as they write standards to counter it. For example, in establishing standards for ballistic resistance of protective vests, a working group developing standards for contract guards should be considering the same weapons as a working group considering ballistic protection around a screening area. (U.S. Department of Homeland Security, 2010a, p. 2)

However, most of the 31 threat scenarios included in the DBT are vague and immeasurable. Without specific and measurable criteria in the design scenarios, it is impossible for a FSC or designer to evaluate if the security objective can be achieved. Even the arson threat scenarios were inconsistently characterized in the *Physical Security Criteria for Federal Facilities* standard and two locations within the DBT. Table 15 compares the different arson threat scenarios employed in the documents.

Table 15. ISC Arson Threat Scenarios (After: U.S. Department of Homeland Security, 2010a)

Source	Page	Threat Description
Physical Security Criteria for Federal Facilities	72	An attack against a government facility by knowingly and willingly setting a fire with intent to cause damage or destruction to the facility and/or physical injury or loss of life to the occupants.
DBT	12	Accessing a facility and deliberately setting fire to the facility or to assets within the facility.
DBT	7.2.1	An adversary places an improved IID containing an accelerant and using a delay mechanism adjacent to a facility, but outside the view of security countermeasures.

From a design perspective, each of these scenarios describes a different and unique set of conditions with unspecified outcomes. Therefore, the contention that these events are “specific,” “consistent,” and “detailed” threat scenarios is not substantiated. Given the dynamic nature of fire behavior, these three scenarios might have dramatically different results. For example, the threat description scenarios could range from a disgruntled employee setting fire to his workstation to an adversary tossing a flaming Molotov cocktail from a road onto a nearby airport taxiway where little or no damage might occur. The scenario frameworks should be consistent throughout the DBT since the countermeasures designed to address specific threat scenarios could differ significantly. None of the arson scenarios provides the specific threat characteristics that would enable a FSC or facility designer to select performance standards and countermeasures designed to overcome the threat or consequences.

According to the DBT report, quantifiable measures should be used for the development of countermeasures to defeat or mitigate specific events. “For example, when it is necessary to protect a facility against a vehicle-borne improvised explosive device (VBIED), the *device size specified for VBIED events should be used for engineering calculations*” [emphasis added] (U.S. Department of Homeland Security, 2010a, p. 6). Given the device size, ordnance experts and forensic analysts are capable of

determining the area of influence of a shock wave, detonation or deflagration velocity and pressure, destruction estimates, and casualty predictions within the blast zone (Murray, 1998; U.S. Department of the Air Force, 2006). Thus, when the engineering or scientific data exist to develop countermeasures, they should be employed, including for arson threats where critical elements within the scenarios may be quantified and appropriate countermeasures developed.

Furthermore, the DBT assumes that criminal and terrorist-initiated "undesirable events" are somehow different from other environmental threats. This presupposition is made in the standard without substantiation and without acknowledging that the destructive effects of other threats can be equally damaging to the built environment. According to the DBT, "the events addressed in this document are man-made. Natural hazards such as earthquakes, floods, fire, or wind storms are beyond the scope of this document and are addressed in applicable construction and life safety standards" (U.S. Department of Homeland Security, 2010a, p. 2). This conclusion assumes that the applicable construction and life safety standards are adequate, but the report provides no justification for that finding. In particular—other than events caused by lightning—one could argue that all fires are manmade, either as a result of an intentional act or neglect in employing fire safety practices. To describe fire as a "natural hazard" and ignore its potential effects is short sighted, and to assume that fire prevention and mitigation are addressed satisfactorily in the applicable construction and life safety standards is a conclusion not quantified by the ISC.

Although fire research and engineering are relatively young fields when compared among other scientific disciplines, recognized and validated methods do exist to quantify fire behavior in the built environment, which is discussed in greater detail in Section IV of this study. The ability to quantify fire behavior with some degree of assurance is at the core of performance-based design methods. When the fire threat—regardless if it is the result of a terrorist attack, criminal behavior, or a natural event—can be quantified, adequate permanent countermeasures can be evaluated.

K. SUMMARY

The physical security of federal facilities assumed a new urgency when the Alfred P. Murrah Building was destroyed by a domestic terrorist attack in 1995. Since then, several federal agencies have developed a variety of security and construction standards intended to enhance safety for occupants, operations, and the non-military facilities themselves. Initially, these standards were intended to counter terrorist attacks using explosive devices, but have evolved into covering a broad range of criminal and terrorist threats. Over time, responsibility for the development and maintenance of these standards was assigned to an ISC within the DHS.

As they developed, most of the physical security standards cited in this section were built upon a prescriptive foundation; guiding agencies to achieve a desired level of protection by giving precise design and construction advice. Since 2008, the standards have begun a slow process toward the development and implementation of performance-based countermeasures. An important next step is to quantify critical elements within the threats—especially arson—in terms that the engineering and design community can translate into quantifiable countermeasures.

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IV. DEVELOPMENTS IN CONSTRUCTION METHODS AND CODES IN THE UNITED STATES

For thousands of years, man has provided shelter for his family and belongings by erecting some sort of structure to protect them from the elements. Whether it was a rude hut or sophisticated multi-story building, these creations became part of the human landscape known as the built environment. This built environment is susceptible to any number of natural or manmade threats including earthquake, weather, fire, rodent and insect vectors, explosion, tsunami, hazardous material release, criminal enterprise, or terrorist attack. This section explains recent developments in regulations intended to strengthen the built environment in the United States, and explores the differences between traditional prescriptive and contemporaneous performance-based designs and codes.

Initially, building construction relied on craftsmen who translated their vision or architectural designs into practical, usable, and often breathtakingly beautiful structures. These creations were limited only by the resources at hand: money and labor to build, natural materials, such as wood and stone to create the buildings, and the physical limits of these natural materials to support themselves and the structural loads[53] imposed upon them. As communities grew, however, social demands increased for safety and comfort in the built environment. Sanitation controls were needed to prevent the spread of disease. Structural requirements were implemented to prevent buildings from collapsing during routine use. Fire protection regulations were instituted to prevent conflagrations. Ventilation standards were instituted to improve personal comfort and health. These requirements eventually became fixed in locally enforced regulations and standards called construction codes,[54] more commonly known as building codes.

[53] "Loads" describes additional weights or stresses, both static and dynamic, which are applied to a building during its lifetime. The building itself constitutes a "dead load" that comprises the structural elements, permanent finishes, and attached features, such as air handling equipment and water towers.

[54] Construction codes typically comprise structural framing, plumbing, electrical, mechanical, fuel gas, and fire protection systems that go into the completion of a building.

Building and fire codes[55] frame critical infrastructure protection and resilience requirements. They establish a community's minimum acceptable level of safety and utility within the built environment. Hospitals, government buildings, schools, factories, stores, fire and police stations, warehouses, single-family dwellings . . . all are constructed in accordance with standards of design based on locally adopted and enforced building codes.[56] These documents are intended to prescribe requirements for safety from earthquake, weather, fire, or commonly recognized technological hazards, as well as provide for comfort and sanitation in accordance with recognized health standards.

Granted, an important distinction exists between building design and code compliance. According to Thomas, "codes are minimums set by the community. Designs are comprehensive plans to make the owner and hopefully the users happy" (D. J. Thomas, n.d., p. 3). If architectural and design latitude did not exist, many buildings would be nothing more than utilitarian shelters, and lack the beauty and inspiration of the some of the nation's greatest design achievements. Building designers and tenants are given the freedom to create both practical and striking structures that meet their functional requirements and aesthetic tastes. Generally, the architect or designer may create a building from any materials that can withstand normal operating loads and the effects of threats, such as high winds, snow, earthquake, or fire. While architects and tenants have the autonomy to design structures that meet their operational needs and artistic expressions, many communities imposed regulatory limitations through the adoption and enforcement of building codes in the interest of public and occupant safety. These regulations establish minimum safety levels, and in some circumstances, prescriptive requirements constrain design freedom by setting arbitrary limits on such things as building height, gross floor area, exit travel distances, and the use of specific materials to enhance fire resistance and structural integrity. Borrowed and adapted from

[55] Fire codes often are considered to be "maintenance" codes that prescribe regulations to protect new and existing buildings—and their tenants—from fire during their routine occupancy.

[56] The regulation of building construction generally falls under state and local government police powers. However, it is acknowledged that not all jurisdictions elect to adopt and enforce building codes.

the SFPE (National Fire Protection Association & Society of Fire Protection Engineers, 2000), for the purpose of this study, prescriptive design is:

> an approach where safety is achieved by specifying certain construction characteristics or materials, by limiting dimensions, or by specifying protection systems without referring to how these requirements achieve a desired safety goal. (p. 9)

The distinction between design and codes becomes further complicated when properties owned by the U.S. government are involved. The Commission on Engineering and Technical Systems (Commission on Engineering and Technical Systems, 1989) explained that "Federal agencies are exempt from these state and local building codes (and from zoning laws as well), and are entirely responsible for all aspects of safety and health in their buildings" (p. 2). This freedom enables the federal government to set its own standards for design and safety. However, the Public Buildings Act of 1988[57] specified that any building constructed or altered by the GSA or any other federal agency should be in compliance—to the extent feasible as determined by the GSA administrator—with the latest published edition of one of the nationally recognized model building codes (Legal Information Institute, 2011a). The GSA administrator may elect to decide that the aesthetic and iconic value of a particular design outweighs the feasibility of complying with building safety codes. This decision may be especially opportune when trying to apply current construction codes to historic public buildings, many of which may have been erected before specific regulations were conceived, developed, or adopted. Ironically, this latter circumstance bodes well for the opportunity to apply performance-based designs where modern prescriptive regulations may be impossible to meet.

A. EVOLUTION OF PRESCRIPTIVE DESIGNS AND CODES

In the United States, regulations that evolved into building codes began as fire prevention and control laws during the colonial era. They were intended to mitigate the

[57] See 40 U.S.C. §3312.

consequences of sparks from chimneys and flames from cooking fires consuming the many wooden structures predominant in that time. Later, in 19th century cities, buildings were constructed so close together they created fire hazards and conflagration potential. The Great Chicago Fire of 1871 that destroyed an estimated 17,500 buildings and killed as many as 300 persons highlighted the need for stronger building and fire codes ("Building Codes," 1994). Many cities adopted their own building and fire safety codes based on their unique conditions of topography, weather, building materials, and construction practices. In 1905, the National Board of Fire Underwriters issued the first model[58] code developed in the United States, the *Recommended Building Code* (later renamed the *National Building Code)* ("Building Code," 1994). Over time, other organizations adopted model construction codes, including the International Conference of Building Officials (1927), the Southern Building Code Congress International (1945), and the Building Officials and Code Administrators (1950). These groups competed for representation in various geographic areas of the United States, but in 1994, the organizations merged into the ICC. Another organization, the National Fire Protection Association, produced a competing set of construction codes and standards.[59]

Historically, building code development is a consensus process, with a nominal scientific or engineering foundation. Persons representing various professional disciplines or commercial interests may serve on one or more technical advisory committees that develop codes and standards to address various elements that affect building construction and safety. Generally, these committees follow specific procedures to assure equal representation of all interested participants—including the general public that may not have a dedicated place on the committee—and majority votes are conducted in accordance with legal and ethical standards to adopt or alter requirements. This democratic approach, Brannigan (2010) claimed, results in building codes that "are legal not essentially technical documents" (personal communication, September 16, 2010). The

[58] A "model" code is one created by one or more interest groups, usually having special expertise in the topic that may be legally adopted by reference by a community that does not have its own code or wishes to adopt regulations similar to other jurisdictions.

[59] "The fundamental difference between a code and a standard is that a code dictates what must be done while a standard spells out how to do it" (Building Technology, 1981).

basis for Brannigan's assertion is that a preponderance of the proposed and adopted code requirements are based on the committee's majority opinion of empirical evidence, and not based on comprehensive scientific inquiry or experimentation. This opinion is shared in a report commissioned by the U.S. Department of Housing and Urban Development, "the process is as much political as technical. Perhaps reflective of our American system of government, the entire process is known as 'voluntary consensus'" (Building Technology, 1981, p. 12). The Building Technology report continues by stating the following..

> The National Building Code through the 1931 edition has explanatory notes, pictures and diagrams throughout. Today, there is only legalese, too much detail, too little policy, no statement of intent, and far too many exceptions to poorly stated generally rules. This lack of clarity is not good for existing buildings because the exercise of flexibility and good judgment is made difficult when the intent is not clear. (Building Technology, 1981, p. 33).

The national code-promulgating organizations[60] rely on committees having various levels of expertise that identify problems, offer solutions, and develop recommendations incorporated into the codes. While scientific and engineering studies about specific building components and their behavior under a variety of conditions may influence the committee recommendations, universal application of these tools to all parts of the building codes does not exist. As far back as 1921, then Secretary of Commerce Herbert Hoover, created a Building Code Committee at the National Bureau of Standards[61] in response to four identified defects in contemporary building laws: 1) they raised the cost of building and made the building industry inactive, 2) they failed to recognize modern methods, 3) they were based on compromises rather than scientific data, and, 4) they lacked uniformity in principles (Building Technology, 1981).

[60] Today, the International Code Council and National Fire Protection Association remain the predominant code and standard promulgating organizations.

[61] The former National Bureau of Standards was a federal research laboratory in the Department of Commerce. In 1988, it became the National Institute of Standards and Technology (NIST).

Most current codes and designs are "prescriptive," in that they prescribe specific minimum rules and features to which building designs must adhere. These regulations can run to hundreds of pages of very explicit criteria. Every building is assigned a "use" and "occupancy" class that establishes the framework for code compliance. For example, according to the *International Building Code* (International Code Council, 2009), a "place of public assembly" is defined as a building where "50 or more persons gather for the purpose of worship, entertainment, drinking and dining, education, awaiting transportation, or deliberation."[62] Given this definition, do all "places of public assembly" have the same inherent hazards? Does the McDonald's restaurant on the street corner have the same safety risks as New York's Radio City Music Hall? Both meet the definition of "places of public assembly," but even people who know nothing about codes would reason they do not possess equal threats to life or property because of the number of people who might be inside at any one time or the variety of potential safety hazards that might exist. Why are prescriptive designs and codes a problem? Prescriptive designs and codes employ generic solutions applied to different use and occupancy situations and may not adequately address the overall vulnerabilities, risks, and hazards needed to create a resilient infrastructure. Prescriptive codes also are criticized for increasing construction costs while discouraging evolutionary architectural design and building product innovation.

Significant prescriptive code changes often occur as the result of a tragedy that captures public attention. Following the 2001 World Trade Center attacks where fire fighter access and occupant evacuation were an issue, the model building code was amended to add new construction requirements for special elevators, fire protection systems, and high-performance fire resistant construction in so-called ultra-high-rise buildings that exceed 420 feet (128 m) in height (National Institute of Standards and Technology, 2008). After 100 nightclub patrons died in 2003 in a fast-moving fire in Rhode Island, the model codes adopted requirements for automatic fire sprinklers in

[62] This example is a classic example of empiricism in prescriptive codes. The number of people that creates a defined place of public assembly, 50, has no basis in science. It is an irrational number selected by a consensus committee to establish a benchmark for code compliance.

similar occupancies (Jonic, 2013). Nine fire fighters in Charleston, South Carolina died on June 18, 2007 in a single-story furniture store. The most recent editions of the model building codes have been amended to include requirements for automatic sprinklers in retail stores where highly combustible upholstered furniture is sold (International Code Council, 2012). While each of these events was tragic, the code changes they spawned were based more on emotional response to the incidents than a comprehensive analysis of the fire and life safety threat that all high-rise buildings, nightclubs, or furniture stores pose.

It is important to acknowledge that the national model building codes establish only minimum life safety and fire protection standards. No prohibition occurs that prevents an architect, designer, owner or tenant from providing additional features that may enhance safety and security beyond the minimums specified in the code. As a simple example, the model building codes require office buildings more than three stories high to have two distinct egress paths via stairways. With some unique exceptions, these stairs are required to be physically separate. Thus, if one stairway were compromised, occupants should expect to have an alternate means of escape via the other stairway. Nothing in the building codes would prevent the architect or tenant from providing additional stairways for safety or convenience; those elective features could be added at the owner's discretion.

In addition to their generic scope, prescriptive codes and designs are criticized for discouraging innovation, being inflexible to evolving changes in methods and materials, and unnecessarily increasing design and construction costs. A common criticism of building codes is that they stifle innovation in both materials and design. In the 1970s, several independent and government-sponsored reports were critical of both building codes and how they were enforced. Gauchat and Shodek (1977) found that "by prescribing specific methods and materials of construction specification codes may also protect the interest of certain participant groups in the building industry rather than act in the interest of all. Union and labor groups clearly have a vested interest in some items in a typical specification code" (p. 22). Richards (1977) was critical of the role-building

product developers played in construction regulations. He claimed “innovation in building codes and standards too often is implemented only after producer monopolies are assured no damage will be done to their vested interest, and secondly, that they will benefit from any change” (p. 280). Oster and Quigley (1977), however, found that greater determinants affecting the diffusion of constructional innovation were the educational level of the chief building official, the extent of trade unionism in the study area, and the relative size of construction companies.

Also, prescriptive designs and codes are blamed for increasing construction costs when their requirements might exceed the nature of the threat. In one example cited by a leading industrial risk assurance firm, the “codes can be too restrictive, causing facilities unnecessary expense. For example, the codes could call for the construction of a 3-ft (0.9 m) dike around a flammable liquids tank when a one-ft (0.3 m) containment would suffice [to contain any spills or leaks from the tank]” (“Building Codes,” 1994, p. 8). Prescriptive codes are full of similar examples where accreted requirements added over time increase construction and maintenance costs without concomitant measurable safety improvements. Likewise, prescriptive designs and codes have long been recognized as not flexible enough to address all situations or threats (Frantzich, 1998). Not all hazards and their controls fit well into the traditional prescriptive model. When the semi-conductor fabrication industry evolved in the early 1980s, its chemical hazards and operational processes were so different from anything previously encountered that no one could figure out how to apply traditional building and fire code requirements. Entire new provisions had to be developed to address this new technology.

Perhaps most significant, prescriptive codes have no means to evaluate the success or failure of compliance with their requirements. Torero (2006) found that despite the technical origin and empirical basis of past prescriptive codes, they are incapable of assessing the performance of a building under fire conditions; instead, they simply assume adequate safety levels are met. New York’s World Trade Center complex was a classic example of prescriptive design that proved vulnerable to an unanticipated and evolving threat. Both towers were designed to withstand the routine rigors of

weather, vibration, earthquake, and other loads. They were even designed to survive the impact of an airplane, which they did on September 11, 2001.[63] According to Eagar and Musso (2001), “the early news reports noted how well the towers withstood the initial impact of the aircraft; however, when one recognizes that the buildings had more than 1,000 times the mass of the aircraft and had been designed to resist steady wind loads of 30 times the weight of the aircraft, this ability to withstand the initial impact is hardly surprising” (p. 8). More significant was the deflagration of nearly 24,000 gallons (90,850 L) of jet fuel with the ensuing fire among the building’s normal contents that was the principal cause of the collapse (Eagar & Musso, 2001). The prescriptive design and engineering standards in place when the World Trade Center was built had not anticipated a fire of this magnitude.[64] Furthermore, an early post-incident analysis of the World Trade Center event by the Federal Emergency Management Agency reinforced Eagar and Musso’s findings and added that many of the “structural and fire protection features of the design and construction were found to be superior to the minimum code requirements” (Federal Emergency Management Agency, 2002b, p. 2). Thus, despite evident compliance with prescriptive building code requirements, no way existed to predict these buildings’ performance when attacked by fire in combination with the aircraft impact.

In their article, *Risk Perception in Performance-Based Building Design and Applications to Terrorism-Resistant Design*, Thompson and Bank (2007) argued that:

> As terrorism represents a constantly changing design challenge, it seems unlikely that prescriptive code requirements will be fully effective in countering this hazard. Codes are not intended to be static documents, but must evolve as new information becomes available or new situations arise. PBD is well suited for design issues that deal with evolving, “cutting-

[63] Additionally, the north tower survived a subterranean truck bombing in 1993 that attempted to topple it onto the south tower.

[64] In an eerily prescient comment, a U.S. Department of Housing and Urban Development building regulation report said, “On July 28, 1945, an Army bomber lost in the fog literally flew into the side of the Empire State Building. Though 14 died from the crash and ensuing fire, the building was essentially undamaged. Not that the World Trade Center would collapse under a similar stress, but the factor of safety gained through the inherent overdesign of earlier construction methods and materials is lacking” (Building Technology, 1981, p. 40).

> edge" concepts. PBD is also well-suited to use in a target-specific hazard environment, as appropriate performance objectives can be chosen according to the hazard level of individual buildings. Thus, PBD seems a natural approach for development of an adaptable terrorism-resistant design methodology. (pp. 66–67)

B. PERFORMANCE-BASED DESIGNS AND CODES

One of the key opportunities for protecting lives and increasing resilience in the built environment exists in the adoption and application of building designs and codes that can be customized to address specific threats. Prescriptive codes provide a generic framework, but cannot address all natural or manmade threats. Code compliance alone is no assurance that a building will successfully resist fire damage caused by an accident or a malicious attack. Performance-based designs and codes are outcome-driven, the desired end state is developed and alternative design solutions are offered to meet it.

No universal definition exists for performance-based design. As have many others, Gross (1996) cited the ancient Babylonian Code of King Hammurabi who decreed that if a builder constructed a house and the house fell and killed the occupant, the builder must be put to death, as the first performance-based requirement. However, in more contemporaneous terms, Gross added that the performance concept was often interpreted differently among different users. To some, he wrote:

> it is a concept of qualitative aspirations for buildings without a systematic methodology for analysis and verification. For others, [it] is a concept which requires quantitative analysis and rigorous evaluation that at times discourages those who wish to use the concept when these tools are not available. (Gross, 1996, p. 5)

For the purpose of this study, however, a single working definition is required. The following description is borrowed from the SFPE (National Fire Protection Association & Society of Fire Protection Engineers, 2000):

> performance-based design is an engineering approach to building design based on established safety goals and objectives; deterministic and probabilistic analysis of threat scenarios and quantitative assessment of design alternatives against the goals and objectives using engineering tools, methodologies and performance criteria. (p. 9)

Deterministic analysis is a method of evaluation that presumes the net result will always produce the same outcome or prediction for a given set of identified conditions. Probabilistic analysis, on the other hand, considers the likelihood of different scenarios and the conditions that describe them to draw conclusions on potential losses and consequences (National Fire Protection Association & Society of Fire Protection Engineers, 2000). Performance-based solutions are intended to establish measurable tenant use and occupancy performance objectives—not arbitrary rules—and provide scientific or engineered design solutions to meet them. Alvarez and Meacham (2010) found that one of the main advantages of performance-based design—particularly for fire safety—is that it enables the designer to propose and evaluate options equivalent to other code requirements, but "without imposing undesired constraints on aspects of building design, such as design flexibility, innovation, or maximization of cost/benefit ratio" (p. 2).

Performance-based designs are not limited to fire safety solutions and they can be employed to address a broad range of homeland security issues; the key is for those who have an interest in the building's design and use (the "stakeholders") to quantify the range and scale of potential threats to the building or facility. One performance objective, for example, may be the occupant's desire for reliable continuity of operations; therefore, the design solutions are focused on maintaining operational reliability. This objective may be particularly important to government agencies. Another performance objective may be to create a large open-area building without fire resistive construction or built-in fire protection systems to permit special research and development projects. Prescriptive codes may not permit a project of this scale. The design flexibility to address specific infrastructure protection needs is not intrinsic to prescriptive designs or codes. For example, due to their size and character, most of the unique mega-hotel/casino projects

built in Clark County, Nevada, in the last two decades, employed some combination of performance-based design elements because they could not comply with the limitations of prescriptive methods. In performance-based design, each structure essentially is constructed to its own unique building code.

To provide a legal framework for code enforcement authorities to accept and evaluate proposed performance-based designs, the ICC in 2001 published the *ICC Performance Code for Buildings and Facilities.* The code is intended to provide for "an environment free of unreasonable risk of death and injury from fires" and "an acceptable level of life safety and property protection from the hazards of fire, explosion or dangerous conditions in all facilities, equipment and processes" (International Code Council, 2009). By 2011, 11 states and 54 local jurisdictions in the United States had adopted the *ICC Performance Code for Buildings and Facilities* (J. Gibson, personal communication, May 9, 2011). Despite this effort, in the United States, Hurley (2008) found that its use has not been widely accepted, "anecdotal evidence suggests that performance-based design is used on five to 10 percent of building design projects" (p. 2).

The *ICC Performance Code for Buildings and Facilities* (the *Code*) provides design guidance in two critical areas, descriptions of appropriate "performance groups" for buildings and facilities, and maximum levels of damage that can be tolerated based on the magnitude of specific events. The relationship between performance groups and event magnitude is explained in subsequent text. First, Table 16 summarizes the four performance group classifications that rate buildings and facilities based on their significance to the community in which they are located.

Table 16. ICC Performance Code for Buildings and Facilities Performance Group Classifications (After: International Code Council, 2001)

Performance Group	Use or Occupancy for Specific Buildings or Facilities
I	Agricultural facilities, temporary facilities and minor storage facilities.
II	All buildings and facilities except those listed in Performance Groups I, III or IV.
III	Buildings and facilities that represent a substantial hazard to human life in the event of a failure, including, but not limited to: 1. Buildings or facilities in which more than 300 people congregate in one area. 2. Elementary schools, secondary schools or day care facilities with a capacity more than 250. 3. Health care facilities with a capacity of more than 50, but lacking surgical or emergency treatment capacity. 4. Jails and detention facilities. 5. Power generation, water treatment, or other public facilities not included in Performance Group IV.
IV	Buildings and facilities designated as essential facilities, including but not limited to: 1. Hospitals and other health care facilities with surgical or emergency treatment capacity. 2. Fire, rescue, and police stations and emergency vehicle garages. 3. Designated emergency preparedness, communication and operations centers, and other facilities required for emergency response. 4. Buildings and facilities having critical national defense functions. 5. Essential utilities for back-up power generation and water distribution for fire suppression.

Although federal government facilities are exempt from locally adopted building and fire codes, they most nearly represent occupancies described in performance groups III and IV. These performance group descriptors might be used to provide the ISC additional data for their design considerations.

Since building and fire codes represent a community's minimum standards for the risk it is willing to accept, the *Code* includes characteristics of the maximum level of damage to be tolerated, which is the second element in the relationship between performance groups and event magnitude. Levels of impact are characterized as mild, moderate, high, and severe depending upon their effect on structural damage, nonstructural systems, occupants, hazardous materials, and the overall extent of damage (International Code Council, 2001). Third, the magnitude of events—including natural and technological (or manmade) hazards—is the severity of the consequences of potential threats and vulnerabilities as expressed "deterministically or probabilistically according to the best current practice of the relevant profession as published in recognized authoritative documents" (International Code Council, 2001, p. 15). Event magnitude is classified as small, medium, large, and very large.

In combination, the performance groups, levels of impact, and event magnitude define the *Code's* maximum level of damage that can be tolerated. Figure 4 captures these criteria.

Magnitude of Design Event (Increasing Magnitude of Event ⇧)	Increasing Level of Performance ⇨ Performance Groups: I	II	III	IV
Very Large (Very Rare)	Severe	Severe	High	Moderate
Large (Rare)	Severe	High	Moderate	Mild
Medium (Less Frequent)	High	Moderate	Mild	Mild
Small (Frequent)	Moderate	Mild	Mild	Mild

Figure 4. ICC Performance Code for Buildings and Facilities Maximum Tolerated Damage Levels (After: International Code Council, 2001)

Using Figure 4, the maximum tolerated damage level to a building having critical national defense functions (Performance Group IV) must be mild for small, medium, or large events, and only moderate for very large or very rare events.

In the federal environment, where its own construction standards are applicable, they permit performance-based design as an alternative to the prescriptive methods. The ISC *Physical Security Criteria for Federal Facilities* is a significant step toward performance-based fire safe design in federal facilities because it relies on the tenants who possess a stake in building operations and safety to describe their desired protection levels. However, this document addresses only threats it describes as "primarily manmade," and claims other threats, such as earthquake, fire, or storms are beyond the scope of the document and are addressed in other applicable construction standards (U.S. Department of Homeland Security, 2010c).

C. APPLICATION OF PERFORMANCE-BASED DESIGN

The SFPE publishes a model for the application of the performance-based design process, which is an iterative process that begins when a project is proposed and continues through completion. Figure 5 depicts the SFPE performance-based design model. The ISC *Physical Security Criteria for Federal Facilities* standard does not address evaluation methods for the permanent countermeasures it suggests; thus, this thesis is limited to the first six steps of the SFPE model that may provide guidance for the ISC to develop evaluative criteria for trial designs.

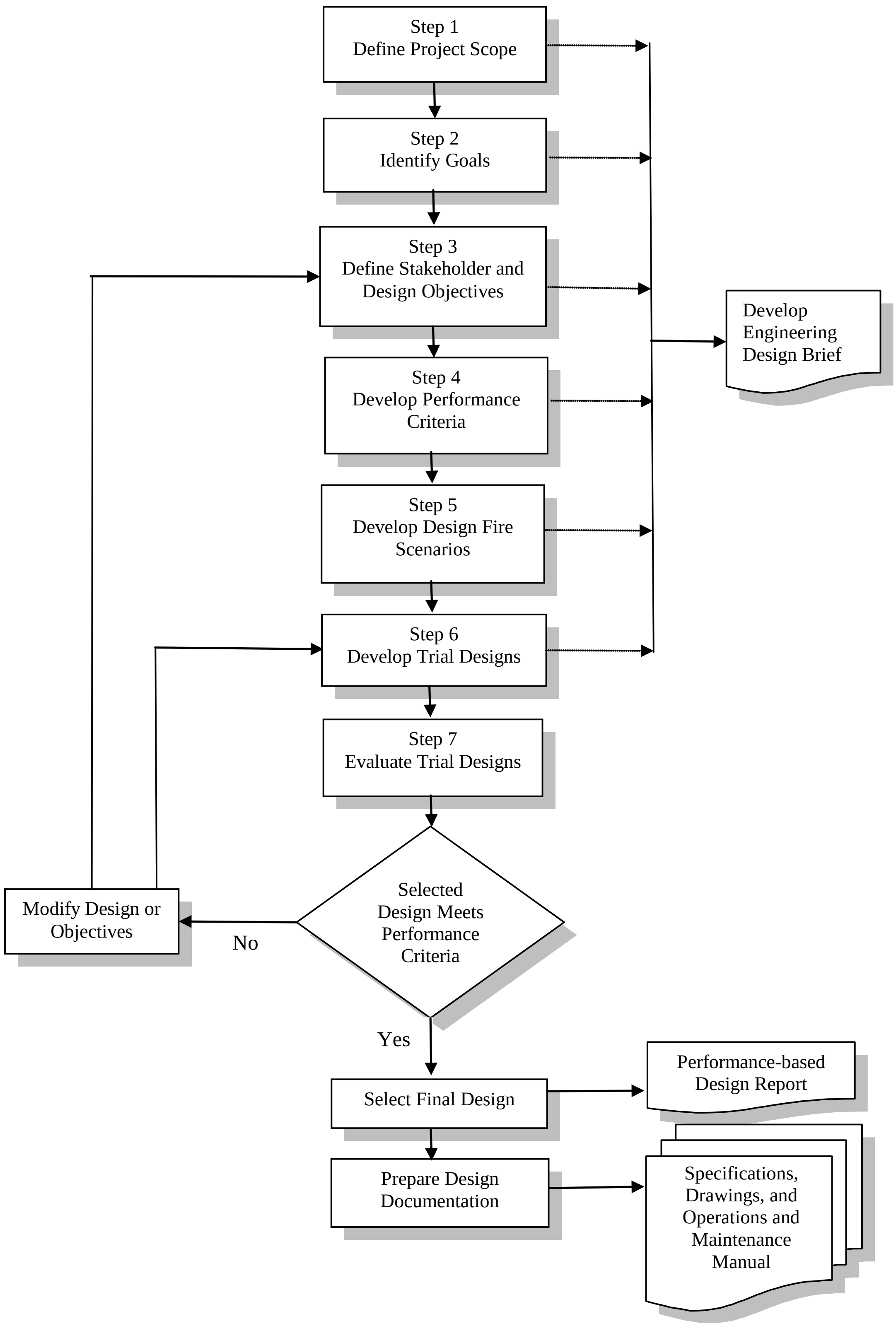

Figure 5. SFPE Performance-Based Design Process Model

The first step in the design process, defining the project scope, is important for the design team and stakeholders to establish fundamental agreement upon what the project will encompass. The composition of the stakeholder group can be project-specific, and can include the building's owner, tenant representatives, architects, interior designers, maintenance personnel, and even neighboring property owners. In the *Physical Security for Federal Facilities* framework, the FSC represents a logical and important stakeholder. Agreement upon the project scope is expected to maximize overall project success. If, for example, the tenant is expecting a major overhaul of their tenant space to improve the office environment for enhanced workflow, but the design team is expecting only to upgrade fire protection features and building services, substantial potential for conflict can occur between the expectations and the outcome. A well-defined and documented project scoping exercise reduces the likelihood of conflict.

In the SFPE model's second step, a stakeholder group establishes project goals. These goals generally are not measurable, but describe the project team's desired outcomes. SFPE (National Fire Protection Association & Society of Fire Protection Engineers, 2000) includes the following model goals for fire safety that are highly applicable to federal properties:

- Provide life safety for the public, building occupants, and emergency responders. Minimize fire-related injuries, and prevent undue loss of life.
- Protect property. Minimize damage to property and cultural resources from fire. Protect building, contents, and historical features from fire and exposure to and from adjacent buildings.
- Provide continuity of operations. Protect the organization's ongoing mission, production, or operating capability. Minimize undue loss of operations and business-related revenue due to fire-related damage.
- Limit the environmental impact of the fire. Protect air and water quality by minimizing emissions and controlling runoff (p. 27).

In the overall project context, the number and scope of stakeholder goals are not limited, and may include such things as minimizing construction costs, maximizing design flexibility, maintaining neighborhood character, employing unique architectural features or materials, or improving pedestrian flow.

Since the goals are non-specific, eventually metrics must be applied to determine if the selected design criteria are appropriate. Refining the goals into stakeholder design objectives is the next step. Stakeholder objectives provide more detail than the goals, and may be described in terms of maximum acceptable or sustainable loss, or the tolerated levels of risk. In some instances, the stakeholder objectives may be clearly articulated. For example, in the goal category of protecting property, the objective might be to confine a fire to the room where it starts. Given this level of tolerated loss, the design team can begin to develop fire protection and construction strategies intended to prevent damage from exceeding the specified level.

Next, quantifiable performance criteria are developed that eventually are used as benchmarks against which various designs can be compared. The performance criteria are related to, but more specific, than the stakeholder design objectives, and include threshold values, ranges of threshold values, or distributions of results from the sample fire scenarios that will be employed (National Fire Protection Association & Society of Fire Protection Engineers, 2000). If the design objective is to confine a fire to the room of origin, one measurable performance criteria might be that the temperature inside the room does not exceed a certain threshold (e.g., 1,112°F [6,000°C]), and the temperatures in adjacent spaces remain at levels that will enable humans to survive (e.g., 135°F [57°C]). These performance criteria are used to provide design guidance for safe egress times, desired fire control, smoke management, or fire protection system performance. While the number of performance criteria is limited only by the stakeholders and design team, it is important to note that as more criteria are added, the design solutions—or what the *Physical Security for Federal Facilities* standard might call *permanent countermeasures* [emphasis added]—become more complex. Furthermore, it is essential to acknowledge, "it is impossible to achieve a completely hazard- or risk-free environment. Additionally, as the level of hazard or risk decreases, the costs associated with those decreasing levels of risk typically increase" (National Fire Protection Association & Society of Fire Protection Engineers, 2000, p. 36). For stakeholders and

the design team, an important part of the performance-based design process is establishing realistic performance criteria that can be achieved within both the project scope and budget.

D. DESIGN FIRE SCENARIOS

A critical component of performance-based design for fire safety is the development of rational fire scenarios that could occur in the building or facility under study. The design fire scenarios are developed and evaluated—often using fire-modeling techniques—to assess the effectiveness of proposed design solutions. According to Hurley and Quiter (2003), the design fire scenarios must be based on the reality of potential fire effects from the nature of the occupancy, the fuel load, potential changes in the property, the presence of fire detection and protection systems, and the purpose for which the design fire is being developed. The lack of a clearly defined and quantifiable design fire is the main deficiency of the DBT arson scenario used in the *Physical Security for Federal Facilities* standard since the following conditions are not quantified "an adversary places an improvised incendiary device (IID) containing an accelerant and utilizing a delay mechanism adjacent to a facility, but outside the view of security countermeasures" (U.S. Department of Homeland Security, 2010c). The IID size and accelerant characteristics are not described and its distance from the facility[65] is not specified. These factors are important in developing permanent countermeasures. Without explicit threat criteria, it is impossible to evaluate whether proposed permanent countermeasures can be or are effective. (It is not clear from the DBT what significance the "delay mechanism" or "outside the view of security countermeasures" play in the fire consequence scenario unless it is anticipated that a delayed ignition or early detection by surveillance would enable an intervention before the IID has a chance to ignite. These elements are outside the scope this study).

[65] Likewise, the facility's construction characteristics (e.g., combustible, non-combustible, or fire resistive) are important to determine the potential consequences of the IID.

The quantification of design fire scenarios is a two-step process. First, a design fire curve is developed that represents the four phases of a fire[66] that might occur in the studied project: ignition, growth, full development, and decay (Hurley & Quiter, 2003). In its simplest portrayal, a design fire curve characterizes the evolving temperature behavior of a fire in a compartment. The ambient room temperature is not significantly altered at the outset by the ignition of a fuel, but as the fire grows and reaches full energy output, the temperature rises until it reaches its maximum based on available fuel and ventilation. As the fuel and oxygen are consumed, the fire eventually enters a decaying state until it loses all energy or is extinguished. The second part of the fire scenario quantification exercise is predicting the potential fire effects from the results of the fire models. These effects may include smoke and fire spread beyond the room of origin, fire growth to structural collapse, occupant tenability, or the operation of fire protection systems.

Since design fire scenarios are expected to represent fires that likely could occur in a building or facility, the fire protection engineering community over time has developed a variety of standardized scenarios against which design professionals can test their proposed life safety and fire protection design solutions. Table 17, which represents design fire scenarios created for the National Fire Protection Association's *Life Safety Code*, is repeated to illustrate some sample design fire scenarios.

[66] Fire behavior is explored in greater detail in Chapter IV.

Table 17. Design Fire Scenarios from NFPA 101, Life Safety Code (After: National Fire Protection Association, 2012)

Scenario	Elements
1	Occupancy-specific fire representative of a typical fire in the occupancy. Explicitly accounts for occupant activities, number, and location, room size, furnishings and contents, fuel properties and ignition sources, ventilation conditions and identification of the first item ignited and its location.
2	Ultra-fast developing fire, in the primary means of egress, with interior doors open at the start of the fire.
3	Fire starting in a normally unoccupied room, potentially endangering a large number of occupants in a large room.
4	Fire originating in a concealed wall or ceiling space adjacent to a large occupied room.
5	A slowly developing fire, shielded from fire protection systems, in proximity to a high occupancy area.
6	The most severe fire resulting from the largest possible fuel load characteristic of the normal operation of the building.
7	An outside exposure fire.
8	Fire originating in ordinary combustibles in a room or area with each passive or active fire protection system independently rendered ineffective.

While these scenarios are included in a nationally recognized model safety code, they are not the only design fire scenarios that might exist. It is incumbent upon the stakeholders and design team to reach a consensus on the variety and scale of potential design fire scenarios that could occur in a specific project under consideration. The range of potential events from the routine to the farfetched may have to be considered, which is what Ripley (2009) called “the unthinkable.” Hurley and Quiter reported that some risk evaluations must be used when developing fire scenarios: “though a fire may be technically plausible, if it is extremely unlikely, that fire may not be necessary to include as a design fire” (2003, p. 3-151). Several design fire scenarios are employed in this thesis to illustrate whether the arson threat scenario in the DBT can be quantified for selecting permanent countermeasures.

As design fire scenarios are developed, the design team must consider that the nature and use of the occupancy may change over time. The initial project assumptions may not remain the same over the life cycle of the building or facility that could affect the original design criteria. For example, if conditions (e.g., spatial configuration, fuel load, fuel array) change, the fire protection features may have to change to match the new arrangement because the original design strategies may no longer perform as expected. While this situation is more problematic in properties under private ownership susceptible to market pressures of sale or lease and change of use, it is a legitimate concern in public facilities as well. Developing the range of potential changes is known as establishing bounding conditions (Hurley & Quiter, 2003) and will be explored in further detail in the section on evaluating permanent countermeasures through risk analysis.

The potential breadth of design fires must be considered as well. Note that in Table 17, all the design fire scenarios begin with a single ignition event. These scenarios do not consider fire's influence as a consequence of another significant event as evidenced by the 2001 World Trade Center aircraft attacks. Writing in *Extreme Event Mitigation in Buildings*, Custer, Marrion, and Johann (in Meacham & Johann, 2006) noted that for fire safety planning and design, it is important to include fires resulting from extreme events, as well as severe events that might occur as a result of a fire. Stakeholders should be encouraged to think freely about potential threats regardless of their immediate plausibility. Multiple IID attacks, a gasoline tanker driven into a building, or a liquefied petroleum gas delivery vehicle detonated adjacent to a structure may be the sorts of extreme events that result in simultaneous significant fires in multiple locations. Fire safety design in the current prescriptive environment and recommended design fire scenarios are ill suited to protect against these catastrophic threats. Custer, Marrion, and Johann (2006) close their article by writing:

> Evaluating candidate [design] strategies requires development of realistic design fire scenarios that encompass worst-case conditions and rational decision-making techniques based on the risks and consequences of those

> scenarios. This process is critical, because it can help ensure that buildings are designed with attention to the actual fire hazards they may encounter in mind. (p. 266)

E. TRIAL DESIGNS

Once the design team has agreed upon performance criteria and a representative sample of design fire scenarios, the means that might be employed to mitigate the fire impacts are developed through trial building and fire protection system designs[67] (see Step 6 in the SFPE design model, Figure 5). The trial designs may include features from one or more components or sub-systems that comprise the building or facility's physical or operational characteristics, as well as the physical features of fire resistant construction, the use of automatic fire detection and suppression systems, and the operational traits of fire behavior, smoke spread, and occupant behavior and egress (National Fire Protection Association & Society of Fire Protection Engineers, 2000). The trial designs give the design team the opportunity to identify and evaluate a variety of solutions against the performance criteria before committing to a final design. If the trial designs perform within the prescribed criteria and design fires, they are considered to be acceptable designs. This approach gives the design team maximum flexibility in materials and design while not being bound to the restrictions of a prescriptive set of regulations, such as those outlined in the DBT .

F. EVALUATING TRIAL DESIGNS AND PERMANENT COUNTERMEASURES

Unlike prescriptive designs and codes, performance-based design requires critical evaluation to compare expected results to the initial design objectives and performance criteria to satisfy the stakeholders. While the concept of building "safety" is subjective and lacks dimension, according to Frantzich (1998), it can be evaluated by comparing the

[67] Within the context of the *Physical Security for Federal Facilities* standard, the list of permanent countermeasures is the primary menu of solutions from which federal Facility Safety Committees (FSC) and design teams select to satisfy the scenarios in the DBT .

proposed design with accepted solutions or with specified tolerable levels of risk. "Comparing the design solution with acceptable solutions can be performed on three levels:

- Simple handbook solutions, i.e. using prescriptive regulations.
- Calculation on sublevel, for example, evaluating escape time margin.
- Evaluation on system level, i.e., performing a quantitative risk analysis (QRA)." (pp. 314–315)

Performance-based designs often employ design, construction, or material options unique, new, or untested in the traditional regulatory environment. This evaluation provides stakeholders, the design team, and code enforcement officials a level of confidence in the proposed design. One cannot simply argue the design "meets the code," but must show that one or more of the proposed designs will perform in accordance with the criteria specified by the stakeholders. The design professional accomplishes the analysis through a variety of risk analysis techniques intended to enhance reliability[68] and reduce uncertainty. The *Physical Security for Federal Facilities* standard describes risk as "a function of the values of threat, consequence and vulnerability. The objective of risk management is to create a level of protection that mitigates vulnerabilities to threats and their potential consequences, thereby reducing risk to an acceptable level" (p. 20) and the Facility Security Committee is responsible for determining and accepting risk based on the results of the standard's evaluation process (Figure 3).

Frantzich (1998) identified three methods of risk analysis developed by the International Electrotechnical Commission in its International Standard 60300-3-9:[69] qualitative, semi-quantitative, and quantitative. The first, qualitative, is used to identify

[68] In this context, "reliability measures whether a design or system will function as designed or intended" (National Fire Protection Association & Society of Fire Protection Engineers, 2000, p. 89).

[69] The standard, entitled "Dependability management-Part 3: Application Guide-Section 9: Risk Analysis of Technological Systems" was withdrawn by the International Electrotechnical Commission on March 4, 2011.

extreme hazardous events without ranking them to any particular degree of hazard. Frantzich recommended qualitative methods be used as a screening method in a preliminary risk analysis.

Second, semi-quantitative risk analysis methods are used to determine a rank ordering of unwanted events. Hazards are assigned a point value, and then ranked according to some standardized scoring system, such as that used in NFPA 101A, *Manual on Alternative Approaches to Life Safety*. In this method, that Frantzich called indexing, point scheme, or numerical grading, recognized hazards are assessed a numerical value, and the sum of the identified problems determines the overall risk. Finally, in quantitative risk analysis, either a probabilistic or deterministic approach is used to consider all the variables that might influence the outcome of a fire. According to the SFPE (National Fire Protection Association & Society of Fire Protection Engineers, 2000), deterministic analysis is a method of evaluation that presumes for a given set of identified conditions; the net result will always produce the same outcome or prediction. Probabilistic analysis, on the other hand, considers the likelihood of different scenarios and the conditions that describe them to draw conclusions on potential losses and consequences.

In classical risk analysis, total risk is the sum of the products of all events times their consequences. All the anticipated design fire scenarios and their consequences (e.g., injuries, deaths, extent of property damage, business, or service interruption) are considered against the potential frequency of their occurrence. Any elements that might influence fire outcomes—such as inoperable fire protection systems or compromised fire resistive construction features—are factored into the analysis. Historical data on the number of fires in similar properties are used to estimate the frequency of events. The number of variables that must be computed is dependent upon the project scale and the stakeholders' demand for accurate analysis. As more potential scenarios are evaluated, the accuracy of the analysis increases. Given the small data set for arson fires in federal

properties compared to the substantial amount of federally owned or leased resources, the use of classical risk analysis to evaluate design fire performance criteria may underestimate the potential vulnerabilities.

Rather than anticipate every conceivable arson scenario and their potential consequences through classical risk analysis, risk binning analysis can be employed to develop an approximate, quantified risk assessment (National Fire Protection Association & Society of Fire Protection Engineers, 2000). In risk binning analysis, the need to inventory every scenario is lessened, and a greater emphasis is placed on realistic worst-case scenarios ranked according to their likely occurrence. Events are put into categories or bins to provide quantifiable results. Generally, in accordance with acceptable engineering principles, the consequences should cover 95% of all possible event outcomes[70] (National Fire Protection Association & Society of Fire Protection Engineers, 2000). The stakeholders must describe the range of consequences and their value. Table 18 provides an example of how consequences might be ranked by the stakeholders.

Table 18. Possible Consequence-Ranking Criteria (After: National Fire Protection Association & Society of Fire Protection Engineers, 2000)

Consequence Level	**Impact on Humans**	**Impact on Property/Operations**
High (H)	Sudden fatalities, acute injuries, immediately life-threatening situations, permanent disabilities.	Building destroyed, operations and service delivery terminated.
Moderate (M)	Serious injuries, permanent disabilities, hospitalization required.	Building uninhabitable, major equipment destroyed, delayed operations functional at another location.

[70] The 95% value is derived from two national consensus engineering standards, the *U.S. Guide to the Expression of Uncertainty in Measurement* from the American National Standards Institute, and *Test Uncertainty: Instruments and Apparatus*, from the American Society of Mechanical Engineers.

Consequence Level	Impact on Humans	Impact on Property/Operations
Low (L)	Minor injuries, no permanent disabilities, no hospitalization.	Repairable building damage, some operational downtime, immediate continuity of operations available off site.
Negligible (N)	Negligible injuries.	Minor building repairs required, minimal operational downtime.

In addition to ranking the consequences, risk binning analysis requires that the potential event frequency be estimated. In this method, the frequency analysis is based on the likelihood of an event causing damages that exceed the specified consequence (high, moderate, low, or negligible), rather than attempting to predict the occurrence of a specific scenario. Expected frequencies should be based on the analysis of fire incident data combined with professional experience. The *SFPE Engineering Guide to Performance-Based Fire Protection* borrows from the DOE's facility safety analysis reports for the probability formulae employed in Table 19.

Table 19. Sample Frequency Criteria Used for Probability Ranking (After: National Fire Protection Association & Society of Fire Protection Engineers, 2000)

Frequency Description	Frequency Level (Median Time to Event)	Description
Anticipated, expected (AE)	$>1 \times 10^{-2}$/yr (<100 yr)	Incidents that might occur several times during the lifetime of the building (incidents that occur commonly).
Unlikely (Unl)	1×10^{-4}/yr $<f<$ 1×10^{-2}/yr (100-10,000 yr)	Events not anticipated to occur during the lifetime of the facility.[71]

[71] Natural phenomena of this probability class include the severest earthquake, a 100-year flood, or the maximum wind gust possible for the location where the building or facility occurs.

Frequency Description	Frequency Level (Median Time to Event)	Description
Extremely unlikely (EU)	1×10^{-6}/yr <f< 1×10^{-4}/yr (10,000-1,000,000 yr)	Events that probably will not occur during the life cycle of the building.
Beyond extremely unlikely (BEU)	$\leq 1 \times 10^{-6}$/yr (> 1,000,000 yr)	All other incidents.

Once the consequences and expected frequencies have been estimated, they are converted to a relative risk through the creation of a consequence-frequency matrix as shown in Figure 6. Each consequence-frequency combination is assigned a relative risk level from the application of Figure 6, and the results are considered bounding risks; those risks that the stakeholders determine are acceptable based on the prescribed conditions and cover 95% or more of all possible event outcomes.

Frequency→ Consequence ↓	BEU $\leq 1 \times 10^{-6}$/yr	EU 10^{-4}/yr <f< 10^{-6}/yr	U 10^{-2}/yr <f< 10^{-4}/yr	AE $>1 \times 10^{-2}$/yr
High		7	4	1
Moderate	10[a]	8	5	2
Low		9	6	3
Negligible	11		12	

High risk   Moderate risk   Low risk   Negligible risk

[a]The numbers in the boxes are for identification only and do not imply a ranking.

Figure 6. Sample Risk-Ranking Matrix for Risk Binning Analysis (After: National Fire Protection Association & Society of Fire Protection Engineers, 2000)

As an example of how to apply risk binning analysis techniques, the stakeholders may determine that a worst-case arson fire scenario for their building or facility could result in the building being uninhabitable and that major equipment would be destroyed, but that

continuity of operations plans (COOP) could be employed that allow operations to occur at another location. According to the Impact on Property/Operations column in Table 18, the consequences of such an event would be “moderate.” According to the baseline profile from the ISC DBT (2010), the arson threat to federal buildings is high and likely to occur during the life cycle of the building, which means an arson attack is anticipated or expected (See Table 19). In the *Risk-Ranking Matrix for Risk Binning Analysis* (Figure 6), the cell at the intersection of the consequence row and the frequency column would conclude that for this scenario, an arson attack is a high risk to the building or facility.

Another risk assessment tool commonly used in fire protection engineering is the deterministic analysis approach, in which the expected performance of the fire protection features is evaluated against one or more design fire scenarios (National Fire Protection Association & Society of Fire Protection Engineers, 2000). As conditions change during a fire (e.g., ignition, growth, flashover, or maximum heat output), they are plotted on a timeline along with critical events that occur with fire protection features in the building (e.g., smoke detector operation, sprinkler flow, or vent opening). Since it is expensive and time consuming to develop full-scale fire tests to demonstrate these conditions and assess their performance, computer fire models commonly are used as the tool to evaluate fire protection feature performance of the trial designs in the design fire scenarios. The trial designs must satisfy each performance criterion (developed during Step 4 of the SFPE design model) to be considered successful. The number of variables that can be considered in the design fire scenario is significant—and all potential combinations of scenarios cannot be predicted—therefore, an uncertainty factor or safety analysis must be included in the analysis so the stakeholders can determine the acceptable levels of risk that the trial designs may mitigate.

According to the *SFPE Engineering Guide to Performance-Based Fire Protection*, “performance-based fire protection analysis and design relies on current scientific knowledge and the ability to perform accurate technical predictions” (p. 103). Like any discipline, fire protection engineering is in constant flux as the science and engineering knowledge of fire behavior and construction materials evolve. Therefore,

early performance-based designs did not have the benefit of current data or protocols to assure complete accuracy, and today's designs do not enjoy the benefit of future research. Due to complexities in physical and chemical properties, currently, it is impossible to duplicate fire behavior in either laboratory or real-world conditions. While accommodating the evolution of the discipline and building confidence in the performance-based approach, it must be recognized that these variables introduce uncertainty into any analysis. Since the science and engineering of fire behavior are not fully developed, uncertainty remains regarding how fires ignite and grow. Computer fire models used in deterministic analysis, for example, are built upon observed behavior, but are not predictive of any specific scenario. Variables and errors in data inputs into computer model introduce additional uncertainty. The performance of building fire protection features as they interact with heat, flames, and smoke is not fully understood. Human behavior during fires and other emergencies varies with age, risk perception, cognition, socioeconomic status, and mobility; thus, it is impossible to predict how building occupants will respond to threatening conditions (Bryan, 2003). Combined, these uncertainties often demand a conservative approach to building design to increase confidence that safety and fire resistance are achieved, yet uncertainty can be reduced as improvements in measurement and performance criteria specificity are achieved.

G. SUMMARY

In the last 50 years, the means and methods for building design and construction have changed dramatically. Not only have prescriptive designs and codes been modernized to address new building methods and materials, but interest has increased in the practice of performance-based design that emphasizes clearly defined fire safety performance objectives rather than arbitrary rules. It is argued by many that greater adoption of performance-based designs will result in creative architecture, reduced construction costs, and a higher degree of public safety.

Key to the successful application of performance-based design is the requirement to identify stakeholder objectives and their acceptable level of risk, and develop one or

more design solutions to satisfy them. The designs are evaluated against specific fire scenarios, often using sophisticated computer modeling techniques to represent fire behavior in a variety of conditions. It is essential that the fire scenarios are quantified to the extent possible so objective analysis of the trial designs can be accomplished. Since performance-based design and the computer models often used to test design hypotheses are an inexact science, commonly accepted probabilistic and deterministic risk analysis techniques are employed to reduce the uncertainty associated with the proposed designs.

V. FIRE BEHAVIOR

Fire is a complex thermodynamic chemical and physical phenomenon not entirely understood by scientists. The field of fire behavior studies is a relatively young discipline when compared to other scientific endeavors. Although ancient alchemists considered fire one of the earth's fundamental elements, it is now known that combustion is a complex chemical reaction involving fuel (usually carbon or hydrocarbon-based[72]), an oxidizing agent, and a competent heat source. When controlled, combustion is an essential part of day-to-day life; it is used to power motor vehicles, support industrial processes, and maintain environmental comfort. On the other hand, the destructive effects of unwanted fires kill and injure thousands and cause billions of dollars of direct property damage each year in the United States. This section provides an overview of fire behavior in the built environment to provide a framework for the application of fire effects modeling software to the research questions. It is not intended to be an exhaustive discussion of fire chemistry and physics.

A. COMBUSTION

In its simplest expression, fire involves the combination of a fuel, an oxidizing agent, and a competent ignition source in proper proportions to ignite and sustain the combustion process. It is an exothermic chemical reaction that produces enough energy to be perceived by humans or instruments. This energy release is manifested in the form of heat and light.

Fuels can consist of many items in solid, liquid, or gaseous states. Whether the furniture in one's home or office, gasoline in one's motor vehicle, or methane that supplies a heating system, fuel is the source of latent energy that is released when ignited. The range of potential fuels in the built environment is very wide, from simple gaseous hydrocarbons to solids that have high molecular weight and complex chemical

[72] Containing atoms of hydrogen, carbon, oxygen and some nitrogen.

composition. Some of these materials are naturally occurring—such as cellulose—and others are manmade, such as gasoline, acetylene, ethanol, polyethylene, and polyurethane. Critical to fire behavior studies is the understanding that all combustion reactions release energy into the environment. This energy release is described in fire behavior studies as the heat of combustion, or the total amount of heat released when a unit of fuel (at 77°F and normal atmospheric pressure [25°C and 1 bar]) is completely oxidized in controlled conditions (Drysdale, 1998). The energy released is measured in kiloJoules per gram (kJ/g)[73] and is represented by the expression ΔH_c. Table 20 provides a sample representation of the heat of combustion and chemical formulae of specific fuels. (Polystyrene and polyethylene, common manmade components in modern furniture fabrics, are described as possessing variable chemical formulae as a result of differences in manufacturing processes). Higher numerical values represent more potential heat energy that may be released from the fuel; therefore, higher numerical values translate into greater challenges for fire protection systems and suppression forces to control or suppress a fire in these fuels.

Table 20. Heat of Combustion of Specific Fuels (After: Drysdale, 1998)

Fuel	**Chemical Formula**	$\boldsymbol{\Delta H_c}$ **(kJ/g)**
Dextrose	$C_6H_{12}O_6$	15.40
Cellulose[a]	$(C_6H_{10}O_5)_n$	16.09
Ethanol	C_2H_5OH	26.78
Acetone	$(CH_3)_2CO$	30.79
Polystyrene	Variable [b]	39.85
Benzene	C_6H_6	40.00
Kerosene	$C_{12}H_{26}$	43.00
Polyethylene	Variable	43.28

[73] Fire behavior studies commonly are conducted in the International System of Units (SI). See Appendix A for conversion to the United States customary system.

Fuel	Chemical Formula	ΔH_c (kJ/g)
Diesel (Fuel Oil No. 2)	Variable	44.00
Propane	C_3H_8	46.45
Gasoline	Variable	47.30
Methane	CH_4	50.00
Ethene	C_2H_4	50.35

[a]A generic formula for cellulosic materials, such as wood, paper, or cotton.

[b]Many of these products are subject to changes in their chemical formulas during the refining or manufacturing process.

An important distinction in fire studies is the difference between heat and temperature. Heat is the amount of energy transferred from one object to another due to differences in temperature. Temperature, represented by degrees in the Fahrenheit, Celsius, Kelvin, or Rankine scales, is simply a measurement of a material's molecular activity compared to a reference point. As an object or fuel absorbs energy from the environment or another object, molecular activity increases. The change in molecular activity is registered as temperature. Table 21 provides an example of temperatures and the corresponding physical or physiological response.

Table 21. Temperature Examples and Corresponding Physical or Physiological Response (After: Fire Behavior, 2011)

Temperature ºF	Temperature ºC	Response
98.6	37	Normal human oral/body temperature
111	44	Human skin begins to feel pain
118	48	Human skin receives a first degree burn injury
131	55	Human skin receives a second degree burn injury
140	62	Burned human tissue becomes numb
162	72	Human skin is instantly destroyed

Temperature ºF	Temperature ºC	Response
212	100	Water boils and produces steam
284	140	Glass transition temperature of polycarbonate
446	230	Melting temperature of polycarbonate
482	250	Charring of natural cotton begins
>572	>300	Charring of modern fire fighter protective clothing begins
>1112	>600	Temperatures inside a post-flashover room fire

Fuels, especially solids and liquids, may have to undergo a physical change before they can be ignited. For combustion to occur, the combustible constituents of the fuel must exist in a gaseous state during which they can be mixed with oxygen and create a fuel-to-oxygen ratio where they ignite and sustain combustion. Wood products and most liquid fuels, for example, must be heated to release the volatile hydrocarbon elements that eventually burn.[74] This thermal decomposition is known as *pyrolysis*. When the flammable constituents exist in a proportion with oxygen that will sustain combustion, the mixture is known as the *flammable limits* or *flammable range.* If the ratio of fuel to oxygen is too little to burn, the mixture is considered "too lean," and conversely, if the amount of fuel in proportion to oxygen is too great, the mixture is considered "too rich."

Oxidizing agents may exist in solid, liquid or gas phases, and provide the necessary oxygen to support combustion. Fires in the built environment require approximately 15–16% oxygen by volume to sustain combustion, and the air humans breathe contains approximately 21% oxygen by volume;[75] thus, in most building fires, a generous supply of oxygen is available to support combustion. In addition, numerous industrial and production chemicals contain oxygen molecules that can be released during combustion, which therefore adds to the available oxygen in the environment. For

[74] Gaseous fuels, e.g., methane and hydrogen, already exist in the physical state that enables them to mix with oxygen.

[75] The remainder is approximately 78% nitrogen and 1% trace elements.

example, solid inorganic nitrates (sodium nitrate, potassium nitrate, and ammonium nitrate) can melt and release oxygen and cause a fire to intensify. Furthermore, molten nitrates react with carbon-based organic materials "with considerable violence, usually releasing toxic oxides of nitrogen" (Davenport, 2003). A universally familiar example of inorganic nitrates used in criminal or terrorist acts was the 1995 truck bombing of the Alfred P. Murrah Federal Building in Oklahoma City that was destroyed by a mixture of diesel fuel (a hydrocarbon) and ammonium nitrate.[76] In fact, the combination of these products is used routinely as a commercial blasting agent called ANFO, which is an acronym for ammonium nitrate-fuel oil. Other oxidizing chemicals that can easily be found in industrial or retail markets include hydrogen peroxide, potassium chlorate, sodium peroxide, ammonium perchlorate, potassium permanganate, and potassium persulfate (Davenport, 2003).

The number and variety of ignition sources is substantial. Overall, these sources are divided into two major categories, piloted ignition and autoignition (Quintiere, 1998). In piloted ignition, a heat source, such as a spark or flame, ignites the fuel in the presence of the oxidizing agent. An electrical spark igniting gasoline vapors is an example of piloted ignition. Likewise, an IID placed in or near a target by a criminal or terrorist adversary generally employs piloted ignition methods, such as an open flame or spark. Autoignition, in contrast, is ignition that occurs absent a spark or flame, and often is the result of chemical decomposition of fuels. Wet, baled hay is well known for autoignition, and results in what is commonly called spontaneous combustion and is responsible for numerous barn fires in agricultural areas. What is important to remember is that the energy required to ignite flammable mixtures is low—a few tenths of a millijoule[77] (mJ) for mixtures in air—thereby, increasing the likelihood that when a flammable mixture exists, it can be ignited easily (Beyler, 1995). For combustion to occur, four conditions must exist.

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[76] More recently, a fire-induced ammonium nitrate explosion in West, Texas resulted in 14 deaths, including 10 first responders (Karimi& Grinberg, 2013).

[77] Approximately 0.0002388459 calorie. See Appendix A for conversion to the U.S. customary system.

- The fuel must exist in a condition within its flammable range
- The ignition source must have sufficient energy to ignite the target fuel
- There must be contact between the ignition source while the fuel is within its flammable range
- The duration of the contact must be sufficient to exchange energy from the ignition source to the fuel (U.S. Fire Administration, 2010b)

B. FIRE BEHAVIOR AND EFFECTS IN COMPARTMENTS

Given the nearly unlimited potential combinations that exist in fuels, oxidizing agents, and ignition sources, combustion science is complex, and remains a challenging and evolving field of study. While a detailed understanding of the physics and chemistry of fire ignition is important to many parts of the scientific community, for the purpose of this thesis, the effects of sustained, unwanted fires are significant to comprehend the problem being studied.

The term "unwanted fires" describes those events either unanticipated or criminal in nature, and result in some insult to humans or the built environment. When an unwanted fire occurs in an enclosed space,[78] its effects are identifiable by a set of generally deterministic and observable characteristics. Granted, the nature and complexities of interactions among the fuels, oxygen supplies, and ignition sources are almost limitless, but fire behavior can be observed in several consistent ways. Under laboratory conditions, complete combustion results in the total consumption of the fuel, with only heat, carbon dioxide and water vapor being emitted (Drysdale, 1998). However, in the built environment, conditions rarely exist for complete combustion, and therefore, fires will emit burned and unburned constituents that result in smoke and other toxic gases, such as carbon monoxide and hydrogen cyanide. For the purpose of the

[78] When describing fires in the built environment, it is assumed they are occurring in a three-dimensional space that usually consists of a floor, enclosing walls, and a ceiling. While these spaces can assume almost limitless configurations, for the purposes of fire studies, they may be called compartments, envelopes, rooms, or the built environment to represent the spatial relationships.

following summary discussion, it is assumed that adequate fuel, oxygen, and a reliable ignition source exist in appropriate conditions to initiate and sustain a fire within a compartment.[79]

Once ignited, a fire will continue to grow until it reaches extinction by consuming all the available fuel or oxygen in the surroundings (however, is not the same as the laboratory definition of complete combustion), or if the fire is interrupted by suppression efforts. Figure 7 represents the relationship between temperature and time in the various stages of compartment fire development. Note that for illustrative purposes, the x and y axes are dimensionless. Values are dependent on specific fire conditions and the geometry of the compartment.

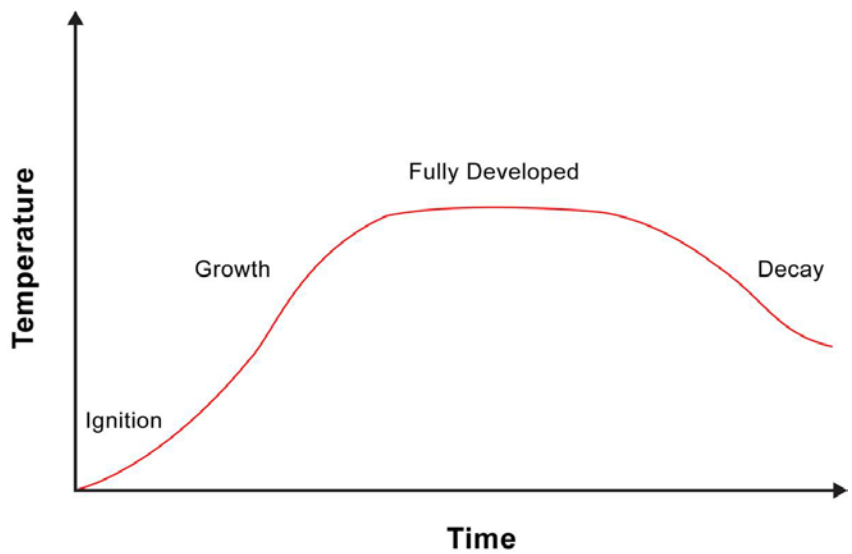

Figure 7. Relationship of Temperature and Time in Compartment Fire Development (From: Fire Behavior, 2011)

As the fire increases in size, and combustible materials decompose through pyrolysis, the ensuing visible flame and smoke become buoyant. This vertical flame spread is called the *fire plume* and delineates the area in which flaming combustion is

[79] Fire behavior may be influenced by the amount of fuel or ventilation available in a compartment, or affected by the operation of a fire protection system, such as an automatic sprinkler system. The multiplicity of possible permutations is outside the scope of this study.

occurring. Heat from the chemical reaction within the plume increases the activity of electrons of the fuel's atoms, and this increased movement results in the emission of energy waves visible to humans (Gorbett & Pharr, 2011). As the hot gases rise, cooler air is induced to flow into the bottom of the fire plume. This process is called entrainment, and is responsible for flame height and turbulence. Temperatures within the fire plume vary across the plume's width with the highest temperatures found at the center of the plume (Quintiere, 1998).

Heat transfer from the fire source to a target, such as furniture, draperies, wall coverings, or other combustible objects, enhances pyrolysis. The amount of energy transmitted to a unit of the target area over a quantified time unit is called heat flux, which is an important measure to determine for whether combustible targets can be ignited. It is normally measured in kilowatts (kW)/m^2, kilojoules (kJ)/m^2 or Btu/ft^2·second. The amount of energy needed to ignite targets varies depending upon the target's ability to absorb heat and its material composition. Table 22 provides examples of materials and the corresponding critical radiant heat flux needed for ignition. Solid fuels are generically classified as *thermally thick* or *thin* depending upon their ability to absorb heat energy and transfer it throughout the object. Based upon their chemical and physical composition, materials need not be physically thicker or thinner than one another, but thermally thick solids absorb heat energy more quickly and do not transfer it as quickly as thermally thin objects do (Gorbett & Pharr, 2011). The likelihood of ignition of thermally thick or thin materials can be predicted through complex mathematical equations.

Table 22. Critical Radiant Heat Flux Needed for Ignition (After: Society of Fire Protection Engineers: Task Group on Engineering Practices, 2002)

Material	Thickness (in.)	Thickness (mm)	Critical Radiant Heat Flux (Btu/ft^2·sec)	Critical Radiant Heat Flux (kW/m^2)
Polymethyl methacrylate[a]	5/8	15.9	0.793	9
Hardboard	1/4	6.35	0.881	10
Carpet, acrylic	NR	NR[b]	0.881	10
Fiber insulation board	NR	NR	1.233	14
Hardboard	1/8	3.175	1.233	14
PMMA (Type G)	1/2	12.7	1.321	15
Asphalt shingle	NR	NR	1.321	15
Douglas fir particle board	1/2	12.7	1.409	16
Plywood, plain	1/2	12.7	1.409	16
Plywood, plain	1/4	6.35	1.409	16
Foam, flexible	1	25.4	1.409	16
Glass-reinforced plastic	1/12	2.24	1.409	16
Hardboard, gloss paint	1/8	3.4	1.497	17
Hardboard, nitrocellulose paint	NR	NR	1.497	17
Glass-reinforced plastic	3/64	1.14	1.497	17
Particle board, stock	1/2	12.7	1.586	18
Carpet, nylon/wool blend	NR	NR	1.586	18
Gypsum board, wallboard	NR	NR	1.586	18
Carpet, wool, untreated	NR	NR	1.762	20
Foam, rigid	1	25.4	1.762	20
Fiberglass shingle	NR	NR	1.850	21
Polyisocyanurate	2	50.8	1.850	21

Material	Thickness (in.)	Thickness (mm)	Critical Radiant Heat Flux (Btu/ft^2·sec)	Critical Radiant Heat Flux (kW/m^2)
Carpet, wool ,treated	NR	NR	1.938	22
Carpet, wool, stock	NR	NR	2.026	23
Aircraft panel, epoxy Fiberite[c]	NR	NR	2.467	28
Gypsum board, fire-rated	1/2	12.7	2.467	28
Polycarbonate	19/32	1.52	2.643	30
Gypsum board, common	1/2	12.7	3.083	35
Plywood, fire retardant	1/2	12.7	3.877	44
Polystyrene	2	50.8	4.053	46

[a]Also known as PMMA, a plastic commonly used in eyewear lenses.
[b]Not reported.
[c]Fiberite is a trade name for a mineral filled epoxy resin.

According to Babrauskas (1983), "especially easily ignitable" items ignite at critical radiant flux of 10 kW/m^2, "normal" ignitability occurs at 20 kW/m^2, while "difficult to ignite" objects correspond to 40 kW/m^2, including primarily slow burning items, such as institutional and office furniture (p. 25).

Flame temperatures in compartments show surprisingly consistent values despite variations in contents and ventilation. Areas may exist in which 1,652°F (900°C) flame temperatures are observed, but wide variations will occur. The peak fire temperature normally associated with compartment fires turns out to be around 2,192°F (1,200°C), although a typical post-flashover room fire will more commonly be 1,652–1,832°F (900 to 1,000°C) (Babrauskas, 2006).

Smoke, which Mulholland (1995) defines as "the smoke aerosol or condensed phase component of the products of combustion," is the visible fire component in which unburned carbon particulate and other toxic gases accumulate (p. 2-217). According to Mulholland, "smoke aerosols vary widely in appearance and structure, from light colored,

for droplets produced during smoldering combustion and fuel pyrolysis, to black, for solid, carbonaceous particulate or soot produced during flaming combustion" (p. 2-217). This description of smoke opacity has important consequences that explain one way heat is transferred in a compartment fire.

In addition to fire spread through direct flame contact, heat energy is transmitted through conduction, convection, and radiation. Conduction is the transfer of heat due to molecular energy; heat is transferred through the material by increased molecular activity. The heat felt when holding a ceramic cup of hot liquid is the result of conductive heat transfer. Convection is heat transfer from a moving fluid (liquid or gas) onto a solid surface, such as what is experienced when holding a hand above an electric or gas cooking range element. Radiation is heat transfer through electromagnetic energy. The heat absorbed from the sun is an example of the effect of radiation.

If a fire possesses adequate energy to reach the ceiling of the compartment, the flames and other products of combustion will travel outward in all directions[80] from the centerline of the fire plume. This horizontal fire spread is called a *ceiling jet* and has a significant influence on heat transfer, as well as fire protection systems, such as detection devices, or automatic sprinklers. As the volume of smoke and heated gases increase in a compartment, the opacity of the smoke affects heat transfer back into the lower levels of the compartment. Mulholland reported in 1995 "a large fraction of the radiant energy emitted from a fire results from the blackbody emission from the soot in the flame" (p. 2-217). This heat energy radiates back into the compartment and increases the rate of pyrolysis of combustible materials. According to Custer (2003), the temperature of the ceiling jet will decrease as its radius increases due to heat losses to the ceiling and to the entrainment of cooler air from the surroundings, and thus. loses energy as it gets farther from the influences of the fire plume.

[80] Assuming the compartment has a smooth, flat ceiling. Ceilings that slope or have architectural features (e.g., beams, soffits, decorations) may affect ceiling jets differently.

As the ceiling jet travels across the surface, the heated gases and other products of combustion interact with the fire protection systems if present. These fire products cause automatic detection devices, such as sprinklers and heat detectors, to respond to thermal changes, and smoke detection devices to sense other products of combustion.

To be usable, spaces within the built environment generally have openings in the form of windows or doors to provide human access or comfort. These openings affect compartment fire behavior by influencing a fire's ventilation and its ability to use oxygen for continued combustion. As the temperature of fire gases increase, they expand and create rising pressure in the compartment.[81] The pressure difference between one compartment and another (or indoors and outdoors) accounts for the movement of smoke and other products of combustion away from the fire source at higher levels of the compartment. Simultaneously, cooler air will enter the enclosure at the lower level, often creating what appear to be two distinct layers of burning and non-burning environments. Over time, this upper layer will descend toward the floor as the volume of smoke increases with continuous combustion. As long as the fire continues to grow and spread, the upper layer descends toward the floor and the fire inside the compartment will maintain positive pressure to push the smoke out. If the fire consumes most of the enclosure's oxygen, however, and begins to subside, the inside pressure will drop below the outside pressure and more air will flow into the space, often resulting in increased combustion, which can occur in a cyclical manner with the result being a compartment fire that appears to be breathing as the air rushes in and smoke pushes out (Gorbett & Pharr, 2011).

Unregulated fire behavior often is characterized as *fuel-controlled* or *ventilation-controlled.* According to Gorbett and Pharr (2011), a "fuel controlled enclosure fire is one that is not adversely affected by the availability of oxygen until the fire nears full-room involvement and is limited only by the availability of fuel in a ready state for combustion" (p. 237). The fire is controlled by the fact that when the fuel is consumed, the fire will diminish toward extinction. A ventilation-controlled fire, on the other hand,

[81] Following the principles of the ideal gas law.

suffers from an inadequate supply of oxygen and may decay toward extinction. Most fires begin as fuel-controlled, but may become ventilation-controlled in the absence of an adequate air or oxygen supply (Gorbett & Pharr, 2011).

Given an adequate fuel supply, a ventilation fire will proceed to burn to *flashover*, the point, according to Thomas (P. H. Thomas, 1983), where the fire transitions from a localized fire to a general conflagration within the compartment in which all fuel surfaces are burning, the fire transitions from fuel-controlled to ventilation-controlled, and there is a sudden propagation of flame through the unburned gases and vapors collected under the ceiling. Depending upon conditions, flashover typically occurs at about 932–1,112°F (500–600°C) and may last several seconds. Peacock, Reneke, Bukowski, and Barbrauskas (1999) concluded that given the wide variety of experimental data, the definition of flashover for fire hazard calculations should include an upper gas temperature of equal to or greater than 1,112°F (600°C) or a heat flux at floor level of greater than or equal to 20 kW/m^2. "After flashover has occurred, the exposed surfaces of all combustible items in the room of origin will be burning, and the *rate of heat release*[82] will develop to a maximum, producing high temperatures" (Drysdale, 1998, p. 325).

According to Babrauskas and Peacock (1992), the HRR is the single most important variable in a fire. HRR describes the amount of heat released over a unit of time by one or more burning objects. The energy release commonly is expressed in watts (W), kilowatts (kW), or megawatts (MW).[83] Generally, HRR provides fire safety professionals a means to quantify fire behavior so it can be compared to other events, especially in computerized fire modeling applications. Babrauskas and Peacock (as cited in Icove & DeHaan, 2009) reported that HRR is "essentially the size or power of the fire. . . .

[82] Also known as heat release rate (identified with the acronym HRR), it is represented by the symbol $\dot{Q}$ where the dot over the Q means per unit time.

[83] A watt is the amount power dissipated by a current of one ampere flowing across a resistance of one ohm. A kilowatt equals 1,000 watts. A megawatt equals 1,000 kilowatts.

> . . . First, and most important, heat released by a fire is the driving force for that fire subsequently to produce more heat by producing more fuel by evaporation or pyrolysis . . . . Second, another important role of the heat release rate . . . is that it directly correlates with many other variables. Examples include the production of smoke and toxic by-products of combustion, room temperature, heat flux, mass loss rates, and flame height impingement.
>
> Third, the direct correlation of heat release rates and lethality of a fire is significant. High heat fluxes, large volumes of high-temperature smoke, and toxic gases may overwhelm occupants, preventing their safe escape during fires. (p. 66)

Table 23 provides examples of peak heat release rates for common objects.

Table 23. Peak Heat Release Rates for Common Objects (After: Icove & DeHaan, 2009, p. 67; Bounagui, Benichou, & Kashef, 2005, pp. 2–3; Madrzykowski, 1996, p. 49)

Material	Peak Heat Release Rate (kW)
Cigarette	.005 (5 W)
Wooden kitchen match or cigarette lighter	.050 (50 W)
Candle	.05–08 (50-80 W)
Bookcase, plywood with aluminum frame	25
Wastepaper basket (0.94 kg)	50
Office wastebasket with paper	50–150
Latex foam pillow (1.24 kg)	117
Small chair with some padding	150–250
Television set (39.8 kg)	290
Modern armchair (41.8 kg)	350 kW–1.2 MW
Recliner with synthetic padding and covering	500–1 000 (1MW)
Natural Christmas tree (7.0 kg)	650
Molded plastic chair (11.26 kg)	700
Metal wardrobe (41.4 kg)	750
Gasoline pool (1.89 L, on concrete)	1 MW
Christmas tree (dry, 1.83 to 2.1 m)	1–5 MW

Material	Peak Heat Release Rate (kW)
Sofa with synthetic padding and covering	1–3 MW
Plywood wardrobe with fabric	3–6 MW
Living room or bedroom (fully involved)	3–10 MW
Office workstation with privacy panels	2.8–6.9 MW

While Figure 7 may represent the fire growth and extinction of a typical compartment fire, current research shows that fire growth and its corresponding energy release is heavily dependent on the nature of the fuel consumed. Citing research conducted by the Factory Mutual Research Corporation, Evans (1995) reported that fire growth and HRR might be assumed to occur in four general categories: ultra-fast, fast, medium, and slow that describe the correlation between time and their maximum HRR. In these categories, the HRR grows proportionately to the square of time, and have become known as t-squared (t^2) fires. According to Fleming (2003):

> In the 1980s, fire protection scientists and engineers introduced the concepts of "slow," "medium," and "fast" t-squared fires to represent a range of expected rates of heat release for fire modeling. Basically, a slow t-squared fire reaches a burning rate of 1,000 Btu/s (1 055 kW) in 600 seconds, while a medium t-squared fire reaches that rate in 300 seconds and a fast fire in 150 seconds.
>
> The concept of the ultra-fast t-squared fire was introduced shortly after the concepts of the slow, medium, and fast fires when it became apparent that the range of those three design fires wasn't sufficient to capture some of the more important fire challenges. The ultra-fast t-squared fire reaches the burning rate of 1,000 Btu/s (1,055 kW) in 75 seconds. (p. 26)

Fleming's comment that the t^2 fires are used in fire modeling explains how in Table 17—Design Fire Scenarios from NFPA 101, Life Safety Code—the various fire scenarios are employed for the purposes of evaluating performance-based designs. Figure 8 illustrates the four t^2 HRR curves with examples of the products tested to obtain the results.

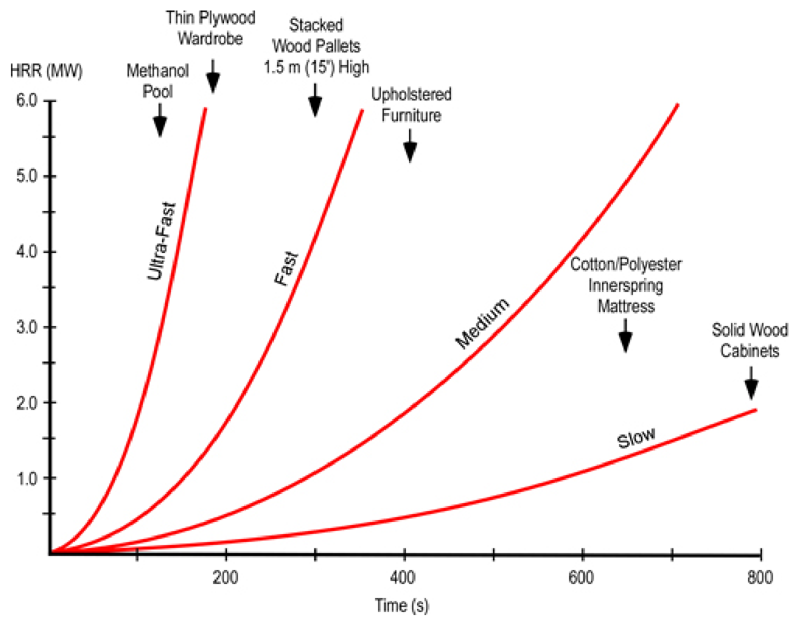

Figure 8. Heat Release Rate (HRR) Curves for Sample t^2 Fires (From: Fire Behavior, 2011)

C. SMOKE AND TOXICITY

While the dramatic visual effect of a fire's flames is impressive, the real threat to human survivability is smoke. According to Hall (2011), between 51% and 73% of fire deaths are attributable to smoke inhalation alone, while the combined effect of smoke inhalation and burns is about 74%. Most fire deaths (85%) occur in residential settings, yet since 2003, an average 109 people die in non-residential fires each year and the data show a recent trend upward (Karter, 2010). This thesis explores these non-residential buildings and facilities in which occupants are assumed to be expected to be awake, alert, oriented to their surroundings, and capable of self-preservation, or by assistance from others.

Smoke is emitted from a fire when the combustion process is not complete, as is typical of most fires outside controlled laboratory environments. Smoke may contain unburned particulate matter, toxic fire gases, water vapor, and other constituents transported away from the fire by convection. Butler and Mullholland (2004) reported that increasing concern exists about the less-than-lethal effects of smoke generated by

fires even in those environments —such as the workplace—in which exposed persons may be fully cognizant of their surroundings and capable of self-preservation.

> The eye and lung irritation due to irritant gases and aerosols and the confusion due to asphyxiants may slow escape or cause incapacitation. The inhalation of a large concentration of soot and toxic gases may lead to lung edema and inflammation, causing death a short time after the fire (p. 149).

The number and potential combinations of lethal and sub-lethal combustion products found in smoke is limited only by the combination of fuels burning and the environment in which they occur. Hundreds of studies have been conducted throughout the world to assess smoke constituents and their lethality (See Levin & Kuligowski, 2005; Gann, 1992; Gann, 2001; Pitts, 2001). According to Purser's review (1995), two critical observations about fire product toxicity are known: 1) in environments in which fires occur, a large number of potentially toxic products occur depending upon the chemical decomposition of the burning material and the available oxygen, and 2) despite the huge potential of variable conditions, "the basic toxic effects were relatively simple. For each individual smoke atmosphere the toxicity was dominated either by a narcotic (asphyxiant) gas [CO or HCN][84] or by irritants" (p. 2-87). Gann (2008) added very succinctly, "of the sublethal [sic] effects of fire effluent, incapacitation is frequently tantamount to lethality. If a person is rendered unable to effect his or her own escape, and if the fire and its effluent continue to spread, the person's survival is threatened" (p. 4).

The toxicity of smoke products generally is described in terms of its lethal concentration and is standardized for comparison by the descriptor $LC_{50.}$.[85] Doses are measured in parts per million in the volume of the compartment under study (ppmv); the lower the LC_{50} value, the more toxic the product. It might be assumed, however, that

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[84] CO is the chemical formula for carbon monoxide, and HCN is the chemical formula for hydrogen cyanide.

[85] The LC_{50} value is the result of statistic calculation based on multiple experiments, each with multiple animals, and indicates the concentration at which 50% of the experimental animals exposed for a specific length of time would be expected to die either during the exposure time of the post-exposure observation period (Levin & Kuligowski, p. 210). For fire toxicity data, the exposure period normally used is 30 minutes (Babrauskas, 1997).

people who are alert and oriented would be expected to evacuate or seek shelter before being exposed to lethal concentrations of toxic gases. According to Babrauskas (1997), concentrations of toxic gases that have a narcotic effect and may incapacitate a person to compromise or prevent the self-evacuation are important, but are problematic to determine. Another value, the hypothetical incapacitation level—referred to as the effective concentration (EC_{50})—has been recommended by National Institute of Standards and Technology (NIST) in reducing the LC_{50} by two to four times. Table 24 lists a few of the known toxic products of combustion and their lethal and effective concentrations.

Table 24. Lethal and Effective Concentrations of Some Toxic Products of Combustion (After: Babrauskas, 1997)

Gas	Assumed[a] human LC_{50} (5 min)	Assumed human LC_{50} (30 min)	Assumed EC_{50} (5 min)	Assumed EC_{50} (30 min)
Carbon dioxide	>150,000	>150,000	--	--
Acetaldehyde	--	20,000	--	--
Ammonia	20,000	9,000	m[b]: 20,000 r: 10,000	m: 4,400 r: 4,000
Hydrogen chloride	16,000	3,700	--	--
Carbon monoxide	--	3,000	--	--
Hydrogen bromide	--	3,000	--	--
Nitric oxide	10,000	2,500	--	--
Carbonyl sulfide	--	2,000	--	--
Hydrogen sulfide	--	2,000	--	--
Hydrogen fluoride	10,000	2,000	--	--
Acrylonitrile	--	2,000	--	--
Carbonyl fluoride	--	750	--	--
Nitrogen dioxide	5,000	500	m: 2,500 r: 5,000	m: 700 r: 300
Acrolein	750	300	--	--
Formaldehyde	--	250	--	--
Sulfur dioxide	500	--	--	--

Gas	Assumed[a] human LC_{50} (5 min)	Assumed human LC_{50} (30 min)	Assumed EC_{50} (5 min)	Assumed EC_{50} (30 min)
Hydrogen cyanide	280	135		
Toluene diisocyanate	--	100	--	--
Phosgene	50	90	--	--
Perfluoroisobutylene	28	6	--	--

[a]All units are reported in parts per million by volume (ppmv).
[b]m = mouse, r = rat.

In a more recent study, using computer modeling,[86] Peacock, Averill, Reneke and Jones (2004) found that for fires that had not reached flashover, within the room in which the fire starts, the incapacitation from heat generally will occur before narcotic gas concentrations reach even 1% of lethal conditions.[87] Importantly, they found that once outside the room of origin—especially in buildings with large rooms—smoke is diluted rapidly and the smoke exposure effects would occur well after a victim is incapacitated by heat. In "residential buildings and other buildings with ordinary size rooms, incapacitation from smoke inhalation will rarely occur before incapacitation from heat and thermal radiation or escape or rescue" (p. 145). This claim is significant and is based on modeling that should be compared to real-world results.

Another concern about smoke is its effect on visual acuity and the ability of people who are trying to escape a fire to negotiate the means of egress to safety. In her 2009 meta-analysis, Kuligowski (2009) found limited visibility caused by smoke could affect both an individual's ability to escape a building with the corollary outcome that a decrease in walking speed could affect both an individual's ability to escape and the subsequent ability to move around a building to perform a work task or tasks. According to Kuligowski's research:

[86] They modeled prototypical ranch house, hotel, and office configurations, all of which comprised one-story scenarios.

[87] "The exception to this involves smoldering fires that generate little heat and, with little buoyancy to drive mixing throughout the space, can readily generate incapacitating exposures, especially for occupants intimate to the smoldering item" (p. 144).

> A high smoke obscuration is likely to affect an individual's safety in a building. Exposures to thick, dense smoke can negatively affect an individual's ability to see their surrounding environment, and in turn, affect their speed of movement throughout a smoke-filled space and their concentration on a job task. The density of the smoke itself affects visibility as well as the irritancy of the smoke. In some cases, irritants can be so potent that individuals cannot open their eyes to see. (p. 31)

The importance of understanding the relationship between smoke toxicity and obscuration is its role in affecting escape time. In the mid-1970s, fire protection professionals began employing the concepts of required safe egress time (RSET) and available safe egress time (ASET). In theory, building occupants—once notified or becoming aware of a threat, such as a fire—required a certain amount of time (the RSET) to respond to the threatening cues and take appropriate action to evacuate the premises. Empirical studies and mathematical human evacuation models led to the ASET concept that measured the amount of time available for egress before the occupant was in imminent danger. If combined fire effects and evacuation models showed that the ASET was less than the RSET (occupants could escape before encountering fire or smoke), the means of egress design was deemed to comply with the performance requirements of the building or fire codes.

According to Chu, Sun, Sun, Chen, and Chen (n.d.) tenability is lost when occupant incapacitation is predicted from exposure to smoke.

> ASET is dominated by ignition, fire growth and the spread of fire and fire smoke. These depend upon a range of variables, such as fire load, the reaction to fire properties of the lining materials and contents, the height and ventilation of the compartment and the characteristics of the fire effluent. (p. 351)

By comparison, "RSET is related to fire detection and alarm, occupant characteristics (such as age, sex, physical and mental ability, sleeping or waking, population density), human behavior in fire (such as seeking information, collecting belongings, choosing an exit) and building characteristics (such as corridor width, exit numbers and widths)" (p. 351). Chu et al. (n.d.) developed a simple timeline diagram to illustrate the relationship

between ASET and RSET (Figure 9). The vertical line at the left of the illustration represents the time at which a fire ignites, and the subsequent events are to the right of this vertical line.

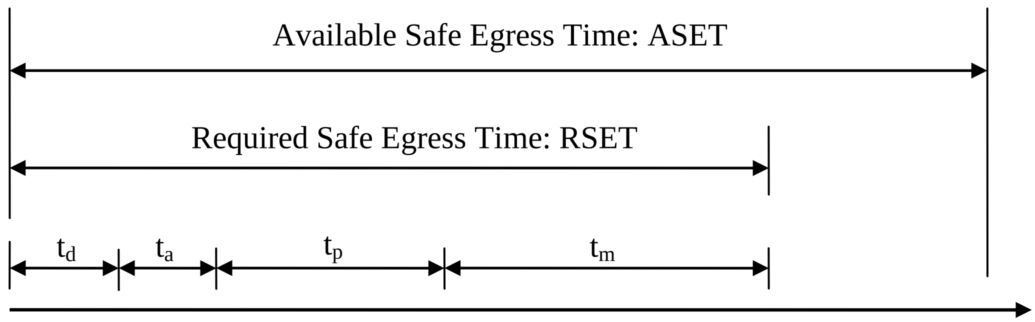

Figure 9. ASET and RSET Comparative Timeline (After: Chu et al., n.d.)

where

t_d = time from ignition to detection

t_a = time to alarm operation and notification

t_p = occupant pre-movement time[88]

t_m = occupant movement time to travel to a place of safety

Recently, Babrauskas, Fleming and Russell (2010) expressed criticism that the RSET/ASET concept was overly simplistic and could not anticipate the broad of conditions, capabilities, and constraints that building occupants might face in fires. Babrauskas et al. (2010) recommended that the RSET/ASET concept be abandoned in favor of other analytical tools that employ a comparative margin of safety analysis, but at this time, those tools do not exist. Chu et al. (n.d.) agreed that for RSET calculations, “occupant pre-movement time is often ignored or oversimplified to be defined as an

[88] The time after an alarm or cue (such as smoke or eyewitness reports of a fire) is evident but before the occupants of a building begin to move towards an exit.

explicit value in fire risk assessment. In fact, occupant pre-evacuation time is not an explicit value but a random variable which follows some probability distribution" (p. 352).

D. SUMMARY

Fire is a complex thermodynamic chemical and physical phenomenon not entirely understood by scientists or fire protection engineers. The almost incalculable combination of fuels, ventilation, and ignition sources, and the nearly limitless potential configurations of building materials and designs, makes detailed scientific analysis complicated. The effects of solid, liquid, or gas fuels, how they are arrayed in a compartment, and their interaction with one another in fire conditions, are subjects for study beyond this thesis. The purpose of this overview is to prepare the reader to be familiar with the data inputs and ranges of possible results that occur in the fire modeling applications of the thesis research.

VI. FIRE AS A WEAPON

Fire has been used as a weapon for millennia. The ease with which it can be started, and the significant damage it can cause, makes it a useful tool to threaten or destroy enemies. News articles and journals continue to be filled with references to using fire as a weapon in a variety of venues. In May 2012, Al Qaeda's English language magazine *Inspire* included a how-to article encouraging adherents to set fires in America's wildland-urban interface to create fright and cause significant economic disruption.

> Our Prophet mentioned to use that the weapon of fright is among the strongest weapons which the Muslim ummah of Muhammad is distinguished with.
>
> . . . fire is one of the soldiers of Allah which He sends upon the disbelievers and controlling it is all cases is impossible, because if the Almighty Allah commanded to destroy, He destroys. (AQ Chef, 2012, p. 35)

A second article in the same *Inspire* issue provided religious justification for arson through a Sharia ruling stating, ". . . it is ok to burn their fortresses with fire, to drown them with water and to ruin and demolish them. . ." (al Nadari, 2012, p. 46).

Despite the fact that in recent years the leading cause of fires in non-military federal buildings was some sort of electrical malfunction, concern still exists regarding malicious acts against federal properties. The sheer number of federal properties and the often-easy access that the public has to them creates a vulnerable environment that is a challenge to protect. According to the ISC DBT , the threat to federal facilities from a fire attack is real.

This section provides an overview of the use of fire as a weapon with IID in the built environment, and looks at some of the current and emerging threats to federal buildings and facilities.

A. FIRE ATTACKS ON FEDERAL FACILITIES

Although its incident data does not clearly identify trends, the federal government considers arson a legitimate security and terrorist threat to its buildings and facilities in the United States. The use of fire as a weapon against federal property is not new. The *Terrorism Threat Handbook* (Interagency OPSEC Support Staff, 2001) reported while only a single arson attack against a U.S. facility and five firebombing incidents were reported in 1998, the following year, six arson attacks and 12 attacks that employed firebombs were reported.[89]

In all types of property, arson in the United States accounted for an estimated 210,300 intentionally set fires each year from 2004 to 2006. Intentionally set fires account for 13% of fires responded to by U.S. fire departments. These fires resulted in an average of approximately 375 deaths, 1,300 injuries, and $1.06 billion in property loss each year (U.S. Fire Administration, 2009). In the GSA's non-military federally owned or leased properties alone, from 2008 to 2010, 55 fires resulted in $10,647,586 damage. More than 5% of these fires were attributed to arson or domestic terrorist attack (J. Elvove, personal correspondence, May 10, 2011). Federal buildings, as iconic targets, are vulnerable to arson attacks by any number of people or organizations that may wish to disrupt government services or make a political or religious statement. The following incidents are just a few of the reported attacks on federal properties.

- In St. Louis on April 25, 2012, a 33-year-old man was charged for firebombing a federal building with a 9.5 oz (281 mL) liquid filled glass container (KSDK, 2012)
- Bottles similar to the one used in the St. Louis attack and sold by a prominent retailer were described by a New York City Bomb Squad technician as the "perfect containers" for a Molotov cocktail:

[89] The report does not define a firebomb nor differentiate between an arson or firebomb attack. The specific locations of these incidents were not reported.

> They are excellent for what you need, because it is a weak-sided bottle with a screw-on cap," Mr. Barry said. "It is small enough to be concealed in your pocket and it fits in your hand, so you can throw it almost like a Nerf football. It's a small projectile you can get a good grip on and you can toss it. (Baker, 2012)

- Two persons were arrested May 20, 2009 in Sacramento, California for leaving an incendiary device inside a paper bag next to the federal courthouse. (News 10/KXTV, 2009)
- On October 4, 2010, a man set fire to the U.S. Probation Office in Plymouth, Massachusetts, causing an estimated $500,000 loss. (Harbert, 2010)
- A non-scientific survey of national news media found anecdotal evidence of arson attacks on federal buildings in five states, attributed to suspects upset about court cases, tax burdens and drug indictments. ("Federal Building Fire," 2008; Legere & Finucae, 2010; "Sprinkler Contains Federal," 1989; Jackson, 1990)
- Buildings in New York's World Trade Center complex that were destroyed by fire on September 11, 2001 housed a diverse group of federal agencies including the Secret Service, Security and Exchange Commission, Federal Home Loan Mortgage Corporation, Equal Employment Opportunity Commission, Central Intelligence Agency, and Internal Revenue Service. ("Building 7's Exclusive," 2007)

The FPS is responsible for the protection of GSA owned and leased properties included in this study. In its 2010 analysis of 625 fire-related incidents, only a single case of arson was reported, and another 64 events were classified as structure fires, unclassified or undetermined origin (M. Harvey, personal communication, August 2, 2011). The DHS Infrastructure Threat Analysis Branch conducted a yearlong study of federal and local courthouses, and determined that while 23 reported cases of threats and other suspicious incidents were reported, none had a nexus to terrorism (Infrastructure Threat Analysis Branch, 2010). The report included two key findings applicable to this study.

- The DHS/Office of Intelligence and Analysis (I&A) has no credible or specific reporting indicating preoperational activity or imminent plans by al-Qa'ida or other terrorist or violent extremist organizations to attack courthouses in the United States
- Based upon an analysis of the threats and suspicious activities . . . , the majority of threats likely were conveyed by individuals intending to delay, cancel, or harass court proceedings (2010, p. 3)

The United States Fire Administration's (USFA) National Fire Incident Reporting Systems (NFIRS) collects data from more than 22,000 local fire departments,[90] but does not permit discretization from that data set of fire incident data by federal property ownership or tenancy. Therefore, it is impossible to determine how many arson fires occurred in federally occupied or controlled buildings or facilities. Table 25 summarizes the most recent three-year period of arson fires for specific property uses in the general U.S. built environment. Table 26 provides data from the GSA.[91]

[90] A fire service census conducted by the U.S. Fire Administration shows that the United States has 64 executive branch fire departments, most of which protect wildland property through the U.S. Forest Service or Department of the Interior. In most cases, non-military federal buildings receive their fire protection services from local fire departments. See http://apps.usfa.fema.gov/census/search.cfm.

[91] Since the NFIRS system does not permit discretization by property ownership, it is acknowledged that some of these events may have been reported by both the local fire services and the separate GSA reporting system. Furthermore, the process of voluntary data submission and processing results in a database is approximately one reporting year behind the current calendar.

Table 25. Fire Incident Data in Selected Property Types, General U.S. Built Environment, 2007–2009 (After: B. Pabody, personal communication, March 27, 2011)

Year	2007			2008			2009			Summary		
Property type	**Total fires**	**Arson fires**	**%**	**Total fires**	**Arson fires**	**%**	**Total fires**	**Arson fires**	**%**	**Total fires**	**Total arson fires**	**Arson % Total**
Office	4,750	247	5.2	4,392	235	5.3	3,852	190	4.9	12,994	672	5.17
Courthouse	129	1	0.07	84	2	2.3	85	6	7.0	298	9	3.02
Total	4,879	248	5.08	4,476	237	5.29	3,397	196	5.7	13,292	681	5.12

Table 26. Fire Incident Data in Selected Property Types, GSA Properties, 2008–2010 (From: J. Elvove, personal communication, May 10, 2011)

Year	2008			2009			2010			Summary		
Property type	**Total fires**	**Arson fires**	**%**	**Total fires**	**Arson fires**	**%**	**Total fires**	**Arson fires**	**%**	**Total fires**	**Total arson fires**	**Arson % Total**
Office	16	1	6.2	11	1	9.1	14	0	0	44	2	4.5
Courthouse	5	0	0	1	0	0	0	0	0	6	0	0.0
Total[a]	21	1	4.8	12	1	8.3	14	0	0	50	2	4.0

[a]Retail and mobile property types have been deleted from the entire GSA data set in this comparison.

Depending upon the data source, the fire and arson data picture among GSA properties is not entirely clear. In comparison to the GSA data, the DBT cites FBI Uniform Crime Reporting data and DHS' FPS records that indicate that from 2007 through 2010, nine arson cases were reported among approximately 9,000 GSA properties.

According to Baird (2006), "historical analysis of incidents coupled with open source information reveals that terrorist groups in general are adapting toward simple destructive methods like arson with increasingly high levels of fatalities" (p. 416). Bjelopera and Randol (2010) found that 19 of 43 homegrown jihadist terrorist plots targeting the United States since September 11, 2001 were involved in whole or in part with explosives or incendiary devices. They concluded:

> Historically, most terrorist incidents in the United States have involved bombs or fires. According to research drawn from the National Consortium for the Study of Terrorism and Responses to Terrorism's Global Terrorism Database, about 83% of all terrorist incidents on U.S. soil between 1970 and 2007—including violent jihadists as well as non-jihadists—have included explosives or incendiary devices. (p. 27)

In contrast, Center for Homeland Defense and Security professor and RAND Institute analyst Dr. Seth Jones offered a qualified assessment that the al Qaeda threat is overstated.

> I have reviewed much of the U.S. government analysis of al Qa'ida leaders, including the interrogations of key leaders (Khalid Sheikh Mohammad, Abu Zubaydah, Abd al-Hadi al-Iraqi, etc.)—and can't remember ever seeing this come up. Many other things do, including attacks against subways, trains, airplanes, etc. Pyroterrorism is, of course, a problem—as is arson more broadly. (personal communication, May 9, 2011)

In its analysis of the arson threat on federal properties, the DBT emphasizes threats from domestic terrorist groups focused on environmental issues: the Animal Liberation Front (ALF) and the Earth Liberation Front (ELF), both of which commonly use fire as their preferred weapon of disruption and destruction (Deshpande, 2009).

> The potential for eco-terrorists and other like-minded extremists to use arson as an attack method, to include IIDs (Improvised Incendiary Devices), makes it likely that this type of attack will continue in the future. The frequency of attacks may increase commensurate with the frequency of Federal properties expanding into wilderness areas. (U.S. Department of Homeland Security, 2010a; U.S. Department of Homeland Security, 2010a, p. 7.2.4)

Similarly, a controversial DHS intelligence assessment on domestic rightwing extremism concluded that economic and political conditions existed in 2009 similar to the 1990s, when the number of domestic rightwing terrorist and extremist groups rose, with a corresponding increase in violent attacks targeting government facilities, law enforcement officers, banks, and infrastructure sectors (Extremism and Radicalization Branch, Homeland Environment Threat Analysis Division, 2009). The intelligence assessment did not speculate on the manifestation or frequency of attacks that might be conducted by these groups.

B. IMPROVISED INCENDIARY DEVICES (IID)

Substantial research exists on IED, especially in the war zones of Afghanistan and Iraq, and as a technique, their use in terrorist attacks on military and civilian populations in densely populated urban areas. While the destructive forces of IED often are the primary concern of federal security professionals trying to protect assets from a terrorist attack, a direct chemical and physical link exists between IED and IID. In fact, many descriptions of IED include references that they contain incendiary or pyrotechnic constituents (Finegan, 2006; Bush, 2007; Wilkinson, Bevan, & Biddle, 2008). The instantaneous oxidation that occurs when an IED explodes is the same chemical reaction that occurs in a fire; only the speed with which the chemical reaction and the ensuing shock wave occur are different.[92]

[92] Explosions often are characterized as “detonations” in which the shock wave exceeds the speed of sound (approximately 786 miles per hour in dry air at 68°F [335 m/s at 20°C]). Sub-sonic shock waves—typically resulting from ignition of volatile flammable liquid vapors—are known as “deflagrations.” Variables, such as relative ambient humidity or the proportion of volatiles to air, can affect these values (Zalosh, 2003).

Furthermore, the instantaneous oxidation of an IED may be the trigger for a secondary, fire bomb-type device. The car bomb parked May 2, 2010 in New York City's Times Square by Faisal Shahzad contained 10 gallons of gasoline and three 25-pound liquefied petroleum gas cylinders ("Faisal Shahzad Sentenced," 2010). As Sweetow (2009) reported, "while many people incorrectly refer to the 9/11 attacks in the colloquial as 'bombings,' they were actually incendiary attacks combining the kinetic energy of fast moving jets with tens of thousands of gallons of jet fuel, to devastating effect" (p. 33). Schubert (2008) contended that flammable fuels—when finely atomized by an accident or primary explosion—can produce pressure waves that result in severe proximal destruction.

Improvised incendiary devices exist in a variety of forms and sizes ranging from handheld containers with simple cloth or paper wicks (famously known as Molotov cocktails) to transportation apparatus and systems that carry a variety of flammable liquids and gases that could be ignited for nefarious purposes. The Internet provides easy access to improvised incendiary device-making instructions in written and video formats ("How to Build an Incendiary Bomb," 2007; Helmenstine, 2011; Dilegge, 2010; How to Make a Bomb," 2011; "How to Make a Fire Bomb," 2009; "Homemade Explosives, Pyrotechnics, Rockets and More!" 2011). While the simplicity of manufacturing and deploying handheld IID makes them a convenient and realistic threat (Romboy & Penrod, 2011; Dize, 2011; Oreg, n.d.; "Man Arrested in Marina del Rey," 2011), attacks on large road, rail, air, and marine transportation vessels carrying flammable and other hazardous cargoes are also a concern (Peterman, Elias, and Fritelli, 2011; Jenkins et al., 2010; Wheeler, 2006). The natural gas pipeline explosion in San Bruno, California—although not the result of a terrorist attack or criminal enterprise—showed that even the fixed transportation networks of hazardous materials could be exploited to create significant fires (U.S. Transportation Security Administration, 2011; Lagos, Fagan, Cabanatuan, & Berton, 2010). The products that fuel U.S. commerce also leave this nation susceptible to improvised incendiary attack.

The use of IID is an increasing concern among homeland security officials, particularly since the scale and scope of the threat is not well articulated. For his Center for Homeland Defenses and Security thesis, Raynis (2006) explored the terrorist use of IID and found that "the homeland security community's intense concentration on the threat posed by IEDs has caused it to overlook the use of IIDs as potentially devastating terrorist weapons. Such a preparedness oversight has created the kind of weakness that terrorists prey on" [sic] (p. 43). Additionally, Raynis (2006) described the simplicity with which IID can be created and deployed.

> Incendiary devices are easily improvised and are inexpensive to produce. The materials to construct an IID are readily available from any hardware or grocery store, and are unlikely to invite suspicion from store employees. There are many advantages to using IIDs as terrorist weapons: they require little training to prepare and use. Overall, flammable materials are not as volatile as explosives; a person using these materials therefore does not require the same level of knowledge and experience as someone handling explosives. (p. 36)

The Transportation Security Administration (TSA) (U.S. Transportation Security Administration, 2008) stated that international terror organizations, affiliated individuals and like-minded or inspired persons, had declared their intent to employ IID against targets in the United States. According to the report, "firebombing, a simple and common tactic among domestic terrorists and criminals, could produce mass casualties and destruction, and create intense fear and anxiety in the public. IIDs are generally improvised more easily and are less expensive the improvised explosive devices" (p. 3). Finegan (2006) drew an even more ominous conclusion, "ignoring emerging threats won't make them go away. If public safety officials apply lessons learned from threat assessment and recognize that our enemies are reacting to our actions, they will quickly realize that ignoring emerging threats will only embolden our enemies and make these types of attacks more likely" (p. 109).

TSA's analysis found that incendiary devices constructed and deployed with strategic placement can cause damage even greater than a similar sized explosive device, because "the fuel may cause a rapidly growing fire that is difficult for first responders to contain, causing an ever-increasing amount of property damage over time" (U.S. Transportation Security Administration, 2008, p. 5).

C. ACCELERANTS

The DBT mentions that the IID presumed to be used in the arson scenario contains an *accelerant*, but like the remainder of the scenario, does not describe it in adequate detail to enable appropriate countermeasures to be developed. In the scenario, the accelerant is the first item ignited and the predominant source of fuel anticipated to threaten the facility. While a scientific consensus for a definition of an accelerant does not exist, the NFPA 921 *Guide for Fire and Explosion Investigations* defines an accelerant as "a fuel or oxidizer, often an ignitible [sic] liquid, used to initiate a fire or increase the rate of growth or spread of fire" (National Fire Protection Association, 2011). According to Babrauskas (2003), accelerants used in incendiary fires are most commonly determined by forensic analysis to be a hydrocarbon-based liquid, such as gasoline, kerosene, paint thinners, solvents, and similar products. In one five-year study, he cited these products were identified as accelerants in 86.9% of debris samples testing positive for accelerants.

Forensic analysis of fire debris for the presence of accelerants usually is performed under laboratory-controlled conditions using gas chromatography-mass spectrometry, a process that enables the laboratory technician to identify a generic product based on its chemical composition or signature. ASTM International, a world-renowned standards development organization, recognizes five test protocols for identifying ignitable liquid residues in fire debris. Once identified, these products may be classified into one of nine major product categories, each[93] having three "weight"

[93] Except that the gasoline category includes gasohol (Stauffer & Lentini, 2003).

subcategories (light, medium, and heavy) based on the number of carbon atoms[94] in their molecular chain. Table 27 summarizes the ASTM International ignitable liquid classification system, and provides generic examples of some common products (Stauffer & Lentini, 2003). Most of these products, in one form or another, are available without restriction on the open market in wholesale or retail environments; thus, they are easily accessible to both legitimate users and potential criminals.

Table 27. ASTM International Ignitable Liquid Classification System with Examples (After: Stauffer & Lentini, 2003)

Class	**Light** **C_4 to C_9**	**Medium[a]** **C_8 to C_{13}**	**Heavy** **C_8 to C_{20}**
Gasoline/Gasohol	Fresh gasoline typically falls in the range of C_4-C_{12}		
Petroleum distillates	Petroleum ether, some cigarette light fluids, some camping fuels	Some charcoal starters, some paint thinners, some dry cleaning solvents	Kerosene, diesel fuel, some jet fuels, some charcoal starters
Isoparaffinic products	Aviation gas, specialty solvents	Some charcoal starters, some paint thinners, some copier toners	Some commercial specialty solvents
Aromatic products	Some paint and varnish removers, some automotive parts cleaners, xylenes, toluene-based products	Some automotive parts cleaners, some specialty cleaning solvents, some insecticide vehicles, fuel additives	Some insecticide vehicles, some industrial cleaning solvents
Naphthenic paraffinic products	Cyclohexane based solvents/products	Some charcoal starters, some insecticide vehicles, some lamp oils	Some insecticide vehicles, some lamp oils, industrial solvents
n-Alkanes products	Solvents, pentane, hexane, heptane	Some candle oils, copier toners	Some candle oils, carbonless forms, copier toners
De-aromatized distillates	Some camping fuels	Some charcoal starters, some paint thinners,	Some charcoal starters, odorless kerosene

[94] Represented in Table 27 as C_n.

Class	Light C_4 to C_9	Medium[a] C_8 to C_{13}	Heavy C_8 to C_{20}
Oxygenated solvents	Alcohols, ketones, some lacquer thinners, fuel additives, surface preparation solvents	Some lacquer thinners, some industrial solvents, metal cleaners/gloss removers	
Others-miscellaneous	Single component products, some blended products, some enamel reducers	Turpentine products, some blended products, various specialty products	Some blended products, some specialty products

[a]ASTM E 1618-01 "Standard Test Method for Ignitable Liquid Residues in Extracts from Fire Debris Samples by Gas Chromatography-Mass Spectrometry," ©2002 permits variations if the carbon number does not fit neatly into a category (Stauffer & Lentini, 2003, p. 65).

The U.S. Department of Justice, Bureau of Alcohol, Tobacco, Firearms and Explosives (BATFE) is authorized under the 1982 Anti-Arson Act[95] to investigate explosions and fires if federal interest in the event is present. BATFE may support state or local jurisdictions in investigations depending upon the nature of the target, victims, property damage death, or injuries (U.S. Department of Justice, 2006). Physical evidence collected by BATFE agents is submitted to its Laboratory Services Division for forensic analysis. From 2000 to 2009, the Laboratory Services Division analyzed 4,485 fire debris samples, and identified residues of ignitable liquids in 2,328 exhibits (A. Blank & R. Kuk, personal correspondence, August 3, 2011). Table 28 provides the distribution frequency of liquids by ASTM classification for the samples analyzed. In nearly two-thirds of the examples, gasoline/gasohol products were found in the fire debris, which clearly makes it the product of choice by adversaries intent on performing criminal acts using accelerants.

[95] See 18 U.S.C. §841.

Table 28. Distribution Frequency of Ignitable Liquids in Federal Arson Debris Analysis, 2000–2009 (After: R. Kuk, personal communication, April 11, 2011)

Class	Positive Results (N= 2,328)	Percentage
Gasoline/Gasohol	1,455	62.50
Petroleum distillates:	--	--
Light (C_4 to C_9)	91	3.91
Medium (C_8 to C_{13})	263	11.30
Heavy (C_8 to C_{20})	345	14.82
Isoparaffinic products	34	1.46
Aromatic products	130	5.58
Naphthenic paraffinic products	24	1.03
n-Alkanes products	56	2.41
De-aromatized distillates	--	--
Oxygenated solvents	123	5.28
Others-miscellaneous	42	1.80

The ignitable liquid data obtained from the BATFE laboratory comport with Babrauskas's 2003 findings that hydrocarbon-based liquids, such as gasoline, kerosene, paint thinners, solvents, and similar products, are the most commonly used accelerants. The findings seem logical since these products are easily available to consumers in retail outlets at which their purchase would not raise undue suspicion.

In a 10-year study of incendiary devices used or recovered in arson cases investigated in the United States by the BAFTE, the U.S. Bomb Data Center collected data on 1,915 IID incidents. Of those events, IID components, such as containers, igniters or main charges, were recovered for processing in 38.3% of the cases (n=735) and containers were recovered in 34.6% (n=662) more cases. Of 517 containers with a reported volume, 77% were less than 64 oz (1,900 mL) in size with the majority being

consumer beer or soda bottles of 40 oz (1,180 mL) of less (J. Oliver, personal communication, August 29, 2011). Table 29 provides a breakdown of the container volumes analyzed.

Table 29. Recovered IID Container Volumes (After: R. Kuk, personal communication, April 11, 2011)

Container Volume (oz)	Container Volume (mL)	Number of containers	% of Total Sample (n=662)	% of Known Container Size (n=517)
64 or less	1900 or less	400	60.4	77.4
Not reported	Not reported	145	21.9	NA[a]
More than 64	More than 1900	117	17.7	22.6
Total		662	100%	100%

[a]NA= Not applicable.

The arson scenario in the ISC DBT describes a threat event where an adversary places an unidentified and non-quantified IID containing an accelerant and utilizing a delay mechanism adjacent to a facility. The data provided by Babrauskas and BATFE suggest the most likely accelerant used in this scenario would be gasoline or another of the commonly available light, medium, or heavy petroleum distillates. However, the quantity and condition remain undescribed; is it a handheld 25 oz. (750 mL) glass bottle that has been broken and spills its contents (e.g., a Molotov cocktail) or is it a large gasoline tanker truck with a capacity ranging from 5,500 to 9,000 U.S. gallons (21,000 to 34,000 L) that is ignited by an incendiary projectile? This information can be significant when conducting fire model analysis of a design scenario, because in addition to the latent heat of combustion of the specific product, the amount and how it is dispersed affects a fire's HRR. According to Babrauskas and Peacock (1992), the HRR is the most important variable in predicting fire behavior in a compartment. Table 30 provides data from the BATFE Laboratory Services Division that compares the HRR at four time points following ignition (30, 60, 90, and 120 seconds) for different amounts and distributions over different areas for some gasoline, kerosene, and heptane samples.

Tests were performed on different volumes of ignitable liquids in open-top vessels of differing size. The liquid depth in the test apparatus was not specified. For illustration, all quantities in the tests exceeded 50.8 oz. (1,500 mL), roughly equivalent to two standard bottles or one magnum of wine found in retail markets. The data are useful to show the differences in HRR for a variety of volumes and configurations; not all burning accelerants emit energy at the same rate. The ISC DBT should consider these variables in its scenario criteria. Of note is that for the configurations tested, 75% reached their peak HRR between 60 and 90 seconds following ignition before tending toward extinction, suggesting that—barring ignition of other objects—protective countermeasures should be employed that will intervene early in the fire, such as automatic fire suppression systems.

Table 30. Heat Release Rates over Time for Varying Hydrocarbon Quantities and Surface Areas (After: R. Kuk, personal communication, April 11, 2011)

Product	**Gasoline**	**Gasoline**	**Gasoline**	**Gasoline**	**Gasoline**	**Kerosene**	**Kerosene**	**Heptane**
Product volume (oz.)	51.5	64.2	103.1	255.9	206.1	51.5	103.1	64.24
(mL)	1,524	1,900	3,048	7,570.8	6,096	1,525	3,048	1,900
Test size (sq. in.)[a]	113.1	254.5	452.3	452.3	1809.5	113.1	452.3	254.5
(cm^2)	729.7	1,641.9	2,918.1	2,918.1	11,674.1	729.7	2,918.1	1,641.9
Time from ignition (sec.)	**Heat Release Rate in kW**							
30	70.81	89.39	281.97	307.51	1,714.11	34.12	19.46	100.46
60	67.52	112.04	387.00	422.49	1,832.02	45.28	197.55	155.81
90	72.24	131.62	365.77	526.82	1,418.55	53.62	281.95	190.02
120	70.44	132.14	370.63	517.02	571.02	52.55	308.32	154.26

[a]The product depth in the test apparatus was not specified.

These BATFE tests were conducted in controlled laboratory conditions. The application of the test results in the built environment in which varying conditions exist for ground or floor surfaces, air movement, humidity, temperature, building construction, and other environmental factors that affect fire behavior should be subject to additional study.

D. SUMMARY

Fire's use as a weapon predates man's recorded history, and remains a destructive force when an adversary uses it to attack persons or property. DHS' ISC assesses the arson threat against federal property to be high, given the unsophisticated nature of the attack method, the historical frequency of its use in general, and specifically, against federal facilities, the availability of specific information on planning, and the ease of executing an attack. However, data variances among the agencies responsible for collecting fire incident information (GSA, FBI, FPS, and USFA) in federal properties do not support the argument that recent historical frequency of arson against federal properties is statistically significant. No doubt exists that determined adversaries may adapt their terrorist or criminal tactics to include fire (Rasmussen & Hafez, 2010; Balachandran, 2011; Dolnik, 2007); however, the threat is not well articulated, which makes it impossible to design effective countermeasures.

In those events in which accelerants are used to increase the rate of fire spread or growth, the preferred materials appear to be commonly obtainable retail products, such as gasoline, kerosene, or solvents. The type, volume, and dispersion effects of the accelerants can affect the outcome of a fire, and should be given thorough consideration in the design of active or passive countermeasures.

VII. METHOD, DATA AND FINDINGS

The development of federal administrative regulations is a complex process involving many—and sometimes competing—interests. The creation of the *Physical Security Criteria for Federal Facilities* standard was the work of participants from more than 20 agencies representing law enforcement, building construction and management, security, diplomacy, intelligence, education, human health, finance, and environmental protection. Given the range of professional disciplines involved, traditional quantitative or qualitative research methods alone may not fully address the breadth, complexity, and synergy of this effort. To get a more complete picture to perform better policy analysis, a variety of research methods is desirable.

The mixed method approach was selected to dissect and evaluate the existing policies (the *Physical Security Criteria for Federal Facilities* standard and its supporting DBT[96]) with the intent of identifying potential shortcomings and improvements. Four research methods were used to build a framework to assess the existing policy documents: 1) an appraisal of GSA, FPS, and national fire and arson incident data, 2) a thematic content analysis of the existing literature pertinent to arson and performance based design practices, 3) a Delphi survey method to formulate a baseline arson scenario, and, 4) the creation of two virtual prototypical federal buildings, then subjecting both designs to simulated fires using state-of-the-art fire effects modeling. A planned fifth method, an online survey of licensed professional architects to obtain design insights, returned so little data as to be worthless.[97]

A. NATIONAL FIRE AND ARSON INCIDENT DATA

Good policy is built on a foundation of solid data. The purpose of reviewing fire and arson information from national incident databases was to obtain a measure of the

[96] The DBT is a separate ISC document that outlines 31 potential threat scenarios against which permanent countermeasures ostensibly can be designed, constructed, and evaluated.

[97] A survey of 118 licensed architectural firms known to the student researcher returned only 10 responses for a response rate of 8.47%, and only seven respondents (5.9%) completed the entire survey. Further research among this target audience was abandoned after a six-week open survey period.

number and characteristics of events that occur in the types of buildings normally owned, occupied, or used by the federal government, and that may be subject to the *Physical Security Criteria for Federal Facilities* standard. Unfortunately, the ability to obtain unconditional data applicable specifically to federal properties is limited by the nature of the publicly available data sources, as well as the inconsistencies among the sources.

Local fire departments and fire marshal's offices are a common source of fire incident data. Due to the longstanding decentralized nature of fire services in the United States, until the 1970s, no comprehensive national database of fire and arson incidents existed. Each fire agency created and maintained its own records management system; no urgent need existed to share data among other organizations. This landscape changed somewhat in 1974 with the adoption of the National Fire Prevention and Control Act (Public Law 93-498) that established a National Fire Data Center (NFDC) to collect and analyze national fire and arson incident data (Ahrens, Stewart, & Cooke, 2003). The USFA is home to the NFDC's NFIRS, a voluntary data collection and assessment system. The NFIRS has two objectives, to help state and local governments develop fire reporting and analysis capability for their own use, and to obtain data that can be used to assess more accurately, and subsequently, combat the fire problem at a national level (U.S. Fire Administration, 2010a). NFIRS collects details about individual incidents to evaluate such factors as fire cause, structure type (e.g., dwelling, school, factory, or office), building construction, nature of the occupants, ignition source, first item ignited, smoke and fire spread, extent of damage, and performance of fire protection systems. This data gives researchers a rich source of information to mine for both trends and anomalies.

Approximately 22,000 of the nation's estimated 27,166 fire departments (U.S. Fire Administration, 2006) report each year through a bottom-up system in which their local fire incident data is sent to a central collection point within their state. The state's combined data is scanned for errors and corrected, and the 50 state agencies and the District of Columbia submit their collated reports to the USFA's NFIRS national database. Due to the time it takes to collect and process the data from the various sources, the most recent data available is from calendar year 2009.

Similarly, local or state law enforcement agencies that may have investigatory responsibilities may voluntarily submit their arson data to the FBI through Uniform Crime Reports (UCR). Data can be submitted in summary form for the so-called Index Crimes,[98] or in detailed form in the National Incident-Based Reporting System (NIBRS). Approximately 6,400 law enforcement agencies participate in NIBRS and 17,000 agencies contribute Index Crime data to the FBI; however, because of computer problems, changes in records management systems, personnel shortages, or a number of other reasons, some agencies cannot provide data for publication (B. Pabody, personal communication, March 27, 2011). According to B. Pabody (personal communication, May 1, 2011), no correlative effort exists between the NFDC and UCR data sets; therefore, in some instances, data may be duplicative. Thus, it is unimaginable to have other than a generic statistical picture of the nation's arson problem.

Another potential data source, the non-profit NFPA, collects data by sampling methods that reached 2,790 fire service organizations in 2010 (Karter, 2012). It then uses statistical methods to estimate the overall number of fires that occur in the United States. As a matter of practice, NFPA does not analyze individual data submitted by fire agencies.

Given the data fields collected in NFIRS, UCR or NIBRS, it is impossible to extract ownership information to identify discrete, federally owned, or occupied properties. Part of the difficulty occurs because federal buildings may be co-located with privately owned real property, or federal agencies may occupy leased space. In its most recent inventory of non-military real property assets, the federal government reported it owned or leased 3.34 billion square feet ($3.1029 \times 10^7 m^2$) in 429,000 buildings (Federal Real Property Council, 2009; U.S. General Services Administration, 2010b). To get a sense of the scale of those combined holdings, 3.34 billion square feet is more than 60,727 times the size of The White House, perhaps the most iconic of all federal buildings. Having the ability to identify federally owned or occupied properties in the

[98] UCR Index Crimes include murder and non-negligent manslaughter, forcible rape, robbery, aggravated assault, burglary, larceny-theft, motor vehicle theft, and arson. NIBRS collects incident data on 33 types of offenses.

entire NFIRS or NIBRS databases would enhance the analytical value of this study, but absent the specific information, generalizations about fire and arson incidents must be interpolated from the general population's data, as well as information provided by the GSA and the FPS.

Unfortunately, data provided by the GSA and the FPS was incomplete and inconsistent. According to J. Elvove (personal communication, May 10, 2011), the GSA does not participate in the NFIRS because the fire service and local government-oriented data NFIRS produces is not entirely applicable to the GSA's property management needs. Furthermore, the GSA does not have clear policies in place that specify when or by whom fire incidents in their properties must be reported. Generally, if estimated property damage from a fire is less than $50,000, no report is required. In some cases, according to Elvove, events may be reported by contractors who may have been responsible for the incident (such as electrical fires or fires caused by careless hot-work roofing practices), but no incentive exists for contractors to provide that information candidly. The GSA's data is current from calendar year 2010. The FPS fire incident data (calendar year 2010) is statistically more detailed—including counts for fires, false fire alarms, fire protection system malfunctions, and unclassified events—but provides little substantive information to enable a comprehensive analysis.

1. Fire Incident and Arson Data

Table 31 provides data comparing fires in federal and non-federal offices and courthouses for the period from 2007 to 2010. Table 32 provides data comparing arson incidents in federal and non-federal offices and courthouses for the period from 2007 to 2010. Since the data ranges collected from these sources (NFIRS, GSA and FPS) is available for only two concurrent years (2008–2009), the ability to perform long-term analysis is limited and the data provides only a general picture of the fire and arson problem in federal properties.

Table 31. Fire Incident Data in Federal/Non-Federal Offices/Courthouses, 2007–2010 (From: Federal property data from J. Elvove, personal communication, May 10, 2011 and M. Harney, personal communication, Federal Protective Service, 2011. All other data from USFA National Fire Data Center, personal communication, March 27, 2011)

Year	**2010**	**2009**	**2008**	**2007**	**Total**
Property type					
Federal offices	14	14	16	NR[a]	44
All other offices	NR	3,852	4,392	4,750	12,994
Federal courthouses	0	1	5	NR	6
All other courthouses	NR	85	84	129	298
Total	14	3,952	4,497	4,879	13,342

[a]NR = Not reported.

Table 32. Arson Incident Data in Federal/Non-Federal Offices/Courthouses, 2007–2010 (From: Federal property data from J. Elvove, personal communication, May 10, 2011 and M. Harney, personal communication, Federal Protective Service, 2011. All other data from USFA National Fire Data Center, personal communication, March 27, 2011)

Year	**2010**	**2009**	**2008**	**2007**	**Total**
Property type					
Federal offices	1	1	1	NR[a]	3
All other offices	NR	190	235	247	672
Federal courthouses	0	1	1	NR	2
All other courthouses	NR	1	2	6	9
Total	1	193	239	253	686

[a]NR = Not reported.

However, other data from these sources does help answer one of the secondary research questions of this thesis: "Should the Interagency Security Committee reports *Physical Security Criteria for Federal Facilities* and the DBT be limited to criminal or "man made" threats as stated in the documents?" Both documents state "other threats to buildings, such as earthquakes, fire, or storms are beyond the scope of this document and are addressed in applicable construction [and life safety][99] standards . . ." (U.S. Department of Homeland Security, 2010a; U.S. Department of Homeland Security, 2010b). According to data presented in Table 2, Ignition Sources for Fires in GSA Federal Facilities 2008–2010, 94.6% of the fires were caused by sources other than manmade, including cooking, electrical, welding or cutting, and other or unclassified.

Federal construction standards—discussed in Chapter VI—since 1988 have mandated compliance with model building and fire codes, and since 1996, have included additional specifications for fire protection and life safety in the form of the "Facilities Standards for the Public Building Service (P100)." The primary goal for the P100 standard is to create conditions that protect occupants and visitors, while the secondary goals are to reduce the federal government and taxpayers' potential losses from fire by protecting real property, maintaining mission continuity, and protecting the environment (P100 standard, p. 235). From 2008 through 2010, only two fire-related fatalities have been reported in federally owned or managed properties, both of which occurred February 18, 2010 when a small aircraft was flown into a building containing an Internal Revenue Service office in Austin, Texas (Brick, 2010). This incident also was responsible for 13 injuries (KVUE and The Associated Press, 2011). Table 33 shows the distribution of fire deaths and injuries in federal and non-federal offices and courthouses for the period 2007 through 2010.

[99] The DBT adds "and life safety" to the text.

Table 33. Fire Deaths and Injuries in Specific Properties, 2007–2010 (From: Federal property data from J. Elvove, personal communication, May 10, 2011 and M. Harney, personal communication, Federal Protective Service, 2011. All other data from USFA National Fire Data Center, personal communication, March 27, 2011)

Year	**2010**		**2009**		**2008**		**2007**		**Total**	
Property type	**Deaths**	**Injuries**	**Deaths**	**Injuries**	**Deaths**	**Injuries**	**Deaths**	**Injuries**	**Deaths**	**Injuries**
Federal offices	2	14	0	2	0	3	NR[a]	NR	2	17
All other offices	NR	NR	0	14	3	34	7	29	10	77
Federal courthouses	0	0	0	0	0	0	NR	NR	0	0
All other courthouses	NR	NR	0	1	0	0	0	6	0	7
Total	2	14	0	17	3	37	7	35	12	101

[a]NR = Not reported.

The secondary goal, reducing property loss and maintaining continuity of operations, is more difficult to quantify and is open to vagaries in subjective analysis. Historically, property fire losses are reported in dollar values of direct and indirect loss, but are not very reliable indicators of the scale of an event. A single room fire that destroys an irreplaceable computer system may cause more direct and indirect monetary damage than an entire warehouse full of printed government forms. Direct loss is the measure of property physically damaged or destroyed during the fire and fire control efforts. However, indirect loss includes intangibles, such as lost business opportunities and lost customers in the private sector, and interruptions to operations or services in the public sector. “Indirect loss could also include dollar equivalents for environmental damage or damage to cultural heritage, but there is no good data source available on these types of indirect damage” (Hall, 2010a). Likewise, according to Ahrens, Frazier, and Heeschan (2003), dollar estimates of property damage are skewed because they involve guesswork or are never reported to the fire department, especially in the case when affected property owners are able to handle the event with on-site resources. To illustrate the wide variety of estimates, Table 34 shows the total reported direct fire loss (not adjusted for inflation) in federal offices and courthouses and non-federal offices and courthouses.

Table 34. Estimated Direct Property Loss Federal/Non-Federal Offices and Courthouses, 2007–2010 (From: Federal property data from J. Elvove, personal communication, May 10, 2011 and M. Harney, personal communication, Federal Protective Service, 2011. All other data from USFA National Fire Data Center, personal communication, March 27, 2011)

Year	**2010**	**2009**	**2008**	**2007**	**Total**
Property type					
Federal offices and courthouses	$3,453,291	$231,000	$6,963,295	NR[a]	$10,647,586
All other offices and courthouses	NR	$65,675,084	$79,742,780	$57,858,791	$204,276,665
Total	$3,453,291	$65,906,084	$86,706,075	$57,858,791	$214,924,251

[a]NR = Not reported.

A less subjective measure, and one that addresses the continuity of operations priorities of the federal government, is the number of incidents when the fire was confined to the room or object of origin. This measure indicates the fire may have self-extinguished before spreading to other objects, was suppressed in the early stages by human intervention, or an automatic fire suppression system, or the nature of the passive fire protection features (e.g., firewalls, doors, and other compartmenting features) confined the fire and limited its effects. By confining the fire to the object or room of origin, less collateral damage occurs and a greater likelihood exists that operations can return to normal more quickly once the damage has been repaired. Table 35 identifies the number of fires in federal and non-federal properties when the incident was confined to the object or room of origin.

Table 35. Fire Incidents where Fire Confined to Object or Room of Origin, 2007–2010 (From: Federal property from J. Elvove, personal communication, May 10, 2011. All other data from USFA National Fire Data Center, personal communication, 2011)

Year Property type	**2010**	**2009**	**2008**	**2007**	**Total**
Federal offices	11	13	15	NR[a]	39
All other offices	NR	623	928	888	2,439
Federal courthouses	0	1	1	NR	2
All other courthouses	NR	18	19	13	24
Total		644	959	897	2,510

[a]NR = Not reported.

When looking at these numbers as a percentage to total events (see Table 36), it is apparent that the outcome of fires in federal offices and courthouses is superior to that of non-federal properties. Fires that occur in federal buildings are more than four times more likely to be confined to the object or room of origin than in non-federal properties.

Table 36. Percentage of Incidents Where Fire Confined to Object or Room of Origin, 2007–2010 (From: Federal property from J. Elvove, personal communication, May 10, 2011. All other data from USFA National Fire Data Center, personal communication, 2011)

Year Property type	**2010**	**2009**	**2008**	**2007**	**Median**
Federal offices	71.5	92.8	93.7	NR[a]	86.4
All other offices	NR	16.2	21.1	18.7	18.8
Federal courthouses	0	100.0	20.0	NR	33.3
All other courthouses	NR	21.4	22.4	2.3	8.1

[a]NR = Not reported.

Additional research is warranted to explain this disparity over what factors are influencing the outcomes[100] between federal and non-federal properties, but given the comparative success of containing fires to the object or room of origin in conjunction with the preponderance of accidental ignition sources in federal buildings,[101] it appears the "applicable construction [and life safety] standards" cited in the *Physical Security Criteria for Federal Facilities* and the DBT are adequate to satisfy the primary goal of life safety and the secondary goals of property protection and environmental controls.

B. THEMATIC CONTENT ANALYSIS OF THE RECENT LITERATURE

Boote and Beile (2005) emphasized the importance of the literature review as a research method because it advances collective understanding about the particular topic being studied, and to enhance that collective understanding an analysis of what has been written previously is required. The literature review is the foundation of any research project to frame its context, clearly demarcates what is and what is not within the scope of study, and justifies the reasons for the structure (Boote & Beile, 2005). In addition,

[100] Among others, factors could include the existence of automatic fire detection and suppression systems, fire resistive construction with automatic opening protectives (e.g., fire doors and dampers), aggressive enforcement of safety rules and regulations, employee continuing training and education, or a cultural commitment to maintaining a safe working environment.

[101] Only 5.4% of fire incidents were classified as malicious.

Leedy and Ormrod (2010) reported that a review of the literature on a particular topic is helpful as its own analytical tool to interpret the results of an individuals' study and relate them to what is already known about the matter being researched.

The purpose of conducting a literature review for this study was to assess whether the performance-based design methods could be employed as effective arson countermeasures, and whether the design criteria published by the SFPE and ICC might be transferable to the *Physical Security Criteria for Federal Facilities* standard to answer the primary and secondary research questions.

A thematic, open-ended content analysis approach was used to assess the current perspective of the literature on performance-based design and its application to arson or incendiary scenarios. A non-probabilistic sample (N = 150) of professional journals and other sources pertinent to building construction was selected, and keyword searches were conducted on one or more combinations of the following terms: building construction, building codes, performance-based design, performance-based codes, fire safety, arson, and incendiary. Both a priori[102] and emergent coding were employed. A priori coding was used to identify the literature source, publication year, geographical source,[103] and fundamental yes/no decisions. Emergent coding evolved early in the literature review to deduce the key criteria authors assigned that described success or failure in their findings. A single coder was used in the literature search. (See Appendix D for the content analysis codebook).

1. Arson Threats Reported in Performance-Based Design Literature

The search showed that arson threats were mentioned in 66.7% (n=100) of the literature pertinent to performance-based design and fire scenarios, including studies that evaluated entire building projects or sub-components, such as fire-resistive construction elements (e.g., structural steel, fire separations, or fire protection systems). In 68.7% (n=103) of the literature, the use of performance-based design was mentioned as a means

[102] Category codes selected before coding began.

[103] Some articles were pertinent to specific countries; others were generic to the engineering discipline and practice of performance-based design.

to craft a viable mitigating solution against incendiary fires. However, substantially fewer of the articles evaluated potential results from the use of performance-based design solutions. Table 37 describes the number of instances in which the potential outcome of the performance-based design option was not addressed in the article, or was determined to be an unsuitable, suitable, or situation dependent option.

Table 37. Performance-based Design Arson Mitigation Suitability Assessment

	n	**%**
Not addressed/no assessment made	102	68.0
Unsuitable	14	9.3
Suitable	10	6.7
Situation dependent	24	16.0
Total	150	100.0

In the 48 instances in which an assessment was made regarding the suitability of performance-based design solutions, one theme emerged as the predominant factor in the method's success or failure, accurate description and quantification of the design fire scenario. The accuracy of the design fire scenario(s) was mentioned as a critical consideration in 34 of the 48 articles (70.8%) where the efficacy of performance-based design solutions was discussed, and was overwhelming cited (83.3%, n=20) in the 24 cases in which the suitability of performance-based design was deemed to be situation dependent. Other thematic issues identified in the literature included whether adequate risk assessments were included in the design proposal (e.g., quantification of the arson threat), the computational power and accuracy of the fire models to mimic complex real world conditions, the competency of the design professionals to interpret the data, and other miscellaneous factors. The results are included in Table 38.

Table 38. Factors Influencing Suitability of Performance Based Design as an Arson Countermeasure

Factor	n	%
Design fire scenario(s)[a]	34	70.8
Adequate risk assessments	5	10.4
Capability of computational tools	4	8.3
User competency	3	6.3
Other	2	4.2
Total	48	100.0

Note. Where more than one factor was mentioned, a simple word count was employed to determine which factor was given primacy by the author.
[a]Three articles used examples of multiple, simultaneous design fires in their analysis.

Thirty-four authors who discussed a well-defined design fire scenario stressed its importance, and their critical criteria varied depending upon the topic of the article. Eleven (32.4%) specifically mentioned the importance of having accurate HRR data to use in fire modeling analysis. Others employed vague descriptions, such as "quantification of the arson scenario," "incomplete scenario development," "scenario definition," or "keep fire scenarios within range of acceptable values," to express the need for accurate data input.

2. References to International Design Documents

Interestingly, given the SFPE's international membership and advocacy on behalf of performance-based design, its *SFPE Engineering Guide to Performance Based Fire Protection* was mentioned in only one (0.7%) of the literature examples pertaining to arson and performance-based design reviewed.[104] Likewise, the ICC's *Performance*

[104] The first edition of the SFPE guide was published in 2000. Fourteen of the articles reviewed (9.4%) were written in 1999 or 2000; therefore, the authors may not have been aware of this document.

Code for Buildings and Facilities was mentioned in a single article, a doctoral thesis regarding the application of systemic dynamics to building simulation for anti-terrorism resource allocation (Thompson, 2009).

Two other documents, *NFPA 101*, *Life Safety Code* and *NFPA 5000 Building Construction and Safety Code*, were referenced in seven and two articles, respectively. These codes permit performance-based design options as alternatives to prescriptive regulations. Both codes employ the eight design fire scenarios of Table 16, Design Fire Scenarios from NFPA 101, Life Safety Code. Scenario 2, "an ultra-fast developing fire, in the primary means of egress, with interior doors open at the start of the fire" arguably is an arson scenario that, according to the NFPA code and its annex, uses gasoline (National Fire Protection Association, 2012). This scenario also is employed in the New Zealand building codes to protect occupants from intentionally set or accidental fires starting in a means of egress (New Zealand Ministry of Business, Innovation and Employment, 2012).

C. BASELINE DESIGN FIRE SCENARIO SELECTION

To obtain a more realistic and quantitative baseline arson scenario than that described in the DBT, a group of expert fire investigators was polled using the Delphi Method. The Delphi Method is an iterative process to collect and distill anonymous judgment from experts using a series of data collection techniques and feedback instruments (Skulmoski, Hartman, & Krahn, 2007). The technique allows the researcher to pose open- and closed-ended questions regarding the topic at hand to a group of subject matter experts. Anonymity in the process allows the participants to express their opinions freely without being influenced by other respondents or the researcher (Rowe & Wright, 1999). When the initial data is collected, the researcher analyzes the results using qualitative coding or statistical summaries to identify commonalities and trends among the responses. Upon completion of the initial analysis, participants complete a second survey based on the first round results, and that survey also is analyzed using the qualitative or statistical method. Generally, a third round of surveys is the final step employed in the Delphi approach.

The baseline design fire scenario Delphi approach employed four main steps: developing the questionnaire, selecting participants, administering the three-round survey, and analyzing the results. One part of the first round questionnaire was used to establish the participants' expert credentials, and the second part was to survey their perception of the likelihood of the arson scenario published in the DBT.

While the word "expert" is subjective, in criminal cases, the presiding judge qualifies expert witnesses individually after a review of the witness's credentials. According to the Advisory Committee on Rules, Rule 702 of the Federal Rules of Evidence states:

> The fields of knowledge which may be drawn upon are not limited merely to the "scientific" and "technical" but extend to all "specialized" knowledge. Similarly, the expert is viewed, not in a narrow sense, but as a person qualified by "knowledge, skill, experience, training or education." Thus within the scope of the rule are not only experts in the strictest sense of the word, e.g., physicians, physicists, and architects, but also the large group sometimes called "skilled" witnesses, such as bankers or landowners testifying to land values. (Legal Information Institute, 2011b) [Electronic edition].

For example, in one study of 693 federal and state criminal appellate court cases over an 11-year period, Groscup, Penrod, Studebaker, Huss, and O'Neil (2002) found that 98% of the experts who testified derived some of their expertise from experience, 74.8% derived some expertise from case specific experience, and 62% derived their expertise through education. Many experts accumulated their expertise from more than one or all of the sources.

Given that expertise is aggregated from experience and education, a 12-question survey was developed to assess respondents' credentials in these realms before asking their suggestions to develop a realistic and quantitative baseline arson scenario. Tables 39 through 41 list the questions and responses used to establish expertise. Survey subjects were 40 volunteer adult students recruited from the *Fire/Arson Origin and Cause*

Investigations and *Interviewing and Interrogation Techniques*[105] courses at the USFA National Fire Academy (NFA) in Emmitsburg, Maryland. Students who attend the NFA represent federal, state, or local government entities responsible for fire protection and post-incident investigation. All students must meet minimum academic criteria and prerequisites, and have the approval of their agency's senior executive to attend the courses. Students who meet the minimum criteria are selected randomly by postal zip code to enhance geographic diversity in the classroom. To recruit the volunteer participants, a classroom instructor not acquainted with this thesis read aloud a recruiting message summarizing the nature and purpose of the study. Subjects were invited to volunteer their participation by proving an email address of their choice to which the survey instruments were delivered. While some students opted to use work email addresses in the format *firstname.lastname@jurisdictionaddress* whereby they potentially could be identified, others provided personal email addresses with no identifying characteristics. In any case, other than the email solicitation to participate in the Delphi surveys, the student researcher had no contact with the subjects to permit their anonymity as much as reasonably possible.

Questions related to subject experience with determining the origin and cause of various fires were derived from National Fire Protection Association 921, Guide for Fire and Explosion Investigations, where:

> Accidental fires involve all those for which the proven cause does not involve an intentional human act to ignite or spread fire into an area where the fire should not be; natural fire causes involve fires caused without direct human intervention or action, such as fires resulting from lightning, earthquake, and wind; [and] an incendiary fire is one intentionally ignited under circumstances in which the person igniting the fire knows the fire should not be ignited. (National Fire Protection Association, 2011, p. 19-1)

[105] The courses address the technical and scientific knowledge and skills needed to conduct successful fire/arson investigations. Methods are demonstrated for conducting legal fire investigations that culminate, when appropriate, in prosecution for arson. Upon the completion of the courses, the students are expected to identify the origin and cause of a fire, conduct a technically and legally sound investigation, and pursue the case through the judicial system (U.S. Fire Administration, 2011).

The three-round survey was conducted between October 21 and January 14, 2012.[106] In each round, subjects were provided an email invitation to participate in the online survey. Forty subjects were invited to participate in the first round of the survey, with a response rate of 55% (N=22). One respondent opted not to participate in the study, and three others did not complete all the data fields,[107] which left 18 respondents (45% of those invited) to supply the data. Table 39, Survey Subjects' Academic Credentials, summarizes the respondents' academic qualifications. Table 40, Survey Subjects' Professional Certifications, identifies the professional certificates they possess.

Table 39. Survey Subjects' Academic Credentials

	Some high school	High School	Trade School	Associates	Bachelors	Masters	Doctorate	No Response
What is the highest level of education you have received?	0	2	2	2	7	6	1	1

Note. N = 21

Table 40. Survey Subjects' Professional Certifications

	n
None	9
International Association of Arson Investigators	10
National Association of Fire Investigators	1
U.S. Department of Justice Bureau of Alcohol, Tobacco, Firearms and Explosives	0
Other	0

Note. N=19. Total equals 20 because one respondent possesses two certifications.

[106] Authorized by Naval Postgraduate School Institutional Review Board Protocol number NPS.2012.0002-IR-EP7-A.

[107] Two of the three who did not complete the entire survey answered questions pertaining to their educational level and certifications.

Table 41, Survey Results: Expert Qualifications, reveals a significant variation in experiential skills among the survey population in the number of structure fires investigated and the number of times the cause of those fires was determined to be accidental. Given the small sampling population, two respondents who reported they had reported between 1,500 and 2,000 fires each heavily skew the data. Regardless, the data shows the respondents are well educated (71.4% possess at least a bachelor's level degree), have an average of 9.05 years of experience in fire investigation, approximately half have been professionally credentialed, and have investigated an estimated 252.05 fires each during their careers.

Table 41. Survey Results: Expert Qualifications

Question	Mean	SD[a]	Median	Mode	Range
How many years of fire and arson investigation experience do you have?	9.05	8.27	5	4	29
What is the number of fire and arson investigation in-service training programs you have attended? (This category includes local, state, national or professional association training programs and seminars where an educational or training component was included.)	28.55	59.91	15	30	262
What is the estimated number of structure fires of all types you have investigated?	252.05	355.35	112.5	300	1994
Of the total number of fires you have investigated, what is the estimated number of incendiary fires you have investigated?	46.64	96.33	25	300	299
What is the estimated number of times you have determined origin and cause of fires that were classified as accidental?	99.5	240.34	50	50	995
What is the estimated number of times you have determined origin and cause of fires that were classified as natural?	8.73	25.88	2	0	100
What is the estimated number of times you have determined origin and cause of fires that were classified as incendiary?	29.77	75.45	12.5	50	300
What is the estimated number of times you have given sworn testimony related to fire and arson investigation, including depositions and courtroom appearances?	19.18	9.79	3	0	300
What is the number of times you have been qualified as a fire investigation expert in state court?	1.59	1.12	0	0	25
What is the number of times you have been qualified as a fire investigation expert in federal court?	1.41	0.86	0	0	25

[a]SD = Standard deviation

In addition to establishing their credentials, in the first round participants were asked[108] to respond to a single closed-ended question and were given the opportunity to submit responses to two open-ended questions. The closed-ended question was captured from the DBT and employed a Likert score to measure responses. The closed-ended question was “In your opinion, how likely is the following arson scenario?” and the description was that found in the DBT: “An adversary places an improvised incendiary device (IID) containing an accelerant and utilizing a delay mechanism adjacent to a facility, but outside the view of security countermeasures.” Ordinal response options included Don’t Know, Highly Unlikely, Unlikely, Neutral/No Opinion, Likely, and Highly Likely, with corresponding scoring values ranging from 0 (zero) to 5 . Table 42 summarizes the responses from the 18 persons who completed the survey.

Table 42. Responses: Likelihood of Design Basis Threat Arson Scenario

Response Option	**Responses**	**%**
Highly Likely	3	16.7
Likely	5	27.8
Neutral/No Opinion	2	11.1
Unlikely	5	27.8
Highly Unlikely	2	11.1
Don’t Know	1	5.6
Total	18	100

[108] Using SurveyMonkey.com.

The distribution of the results shows that respondents were equally divided between the scenario being unlikely or likely, with a small percentage (16.7%, n=3) reporting the scenario to be highly likely.

In the open-ended questions, respondents were asked to complete the following narratives.

- Describe what you believe are likely or highly likely arson scenarios involving non-military and non-postal federal buildings or facilities
- For your scenario(s), describe what you believe would be the first item or items ignited by the perpetrator

The narrative responses were analyzed for key themes and words that resulted in the following nine closed-ended and one open-ended question for the second round of the Delphi analysis. Table 43, Second Round Results: Subject-Suggested Arson Scenarios, shows the nine closed-ended questions and responses. Respondents were asked to employ Likert techniques, and ordinal response options included No Answer, Highly Unlikely, Unlikely, Likely, and Highly Likely, with corresponding scoring values ranging from 0 to 4. The frequency of each response was multiplied by the assigned scoring value, and the sum divided by the number of respondents to obtain the mean. The response rate to the second round of the survey was 35% (n=14), down four respondents from the first round. Table 43 summarizes their responses and ranks them according to the distribution of results. Table 44, Second Round Results: Item Most Likely Ignited First, presents the respondents' data on the eight items they suggested would be the most likely ignited first by an adversary to result in a fire. In this table, the options were cloth or fabric, combustible container, ignitable liquid, light bulb filament, makeshift materials (garbage, rubbish, waste paper), paper or cardboard, a road flare, or other. Respondents were asked to rank them from 1 to 8, with "1" representing the most likely item first ignited, and "8" being the least likely item first ignited by an adversary. In Table 44, a lower mean value represents a higher likelihood of occurrence.

Table 43. Second Round Results: Subject-Suggested Arson Scenarios

Question	Mean	SD[a]	Median	Mode	Rank
An adversary, who is an agency employee, starts a fire.	3.0000	11.46	1	1	1
An adversary uses liquid accelerants on the outside of the building.	2.9286	11.10	2	0	2
An adversary breaks a window and ignites burnable materials that can be reached inside.	2.8585	8.70	3	3	3
An adversary uses a Molotov cocktail thrown through the window or store front.	2.8571	8.69	3	3	4
An adversary hand-deploys incendiary devices (e.g., Molotov cocktail) at facilities with unsecured pedestrian access (sidewalks).	2.6429	7.27	2	0	5
An adversary breaks in and uses flammable liquids as an accelerant.	2.5000	11.45	2	0	6
An adversary places an incendiary fire ignition device around an accessible/unsecured perimeter.	2.2857	5.86	2	1	7
An adversary places the incendiary device in a mail box, homeless persons’ cart or bags, waste basket attached to poles.	2.0714	4.61	2	2	8
An adversary ignites a portable toilet with a road flare, which ignites the adjacent building.	1.6428	6.62	1	1	9

[a]SD= Standard deviation

Table 44. Second Round Results: Item Most Likely Ignited First

Item Most Likely Ignited First	Mean	SD[a]	Median	Mode	Rank
Ignitable liquid	1.86	1.29	1	1	1
Paper, cardboard	2.71	1.14	2.5	4	2
Makeshift materials (garbage, rubbish, waste paper)	3.08	1.31	3	3	3
Cloth or fabric	3.92	1.56	4	5	4
Combustible container	4.36	1.57	5	5	5
Road flare	5.92	1.56	6.5	7	6
Other	6.29	2.43	8	8	7
Light bulb filament	7.00	1.04	7	8	8

Note. "Other" responses included "vehicle," "incendiary device," and "furnishings i.e., bedding, sofa, overstuffed chair, love seat."
[a]SD=Standard deviation

For the final round, the top three results from round two were submitted to the survey subjects. The final round response rate was 42.5% (n=17). Tables 45 and 46 present the final data from the experts surveyed. According to their opinions, the most likely arson scenario in federal buildings or facilities is one in which an adversary breaks a window for entry, and using makeshift materials found on the premises, ignites a fire.

Table 45. Final Round Results: Subject-Suggested Arson Scenarios

Question	Mean	SD[a]	Median	Mode	Rank
An adversary breaks a window and ignites burnable materials that can be reached inside.	2.15	0.69	2	2	1
An adversary, who is an agency employee, starts a fire.	1.87	0.99	1	1	2
An adversary uses liquid accelerants on the outside of the building.	1.85	0.80	2	1	3

[a]SD=Standard deviation

Table 46. Final Round Results: Item Most Likely Ignited First

Item Most Likely Ignited First	Mean	SD[a]	Median	Mode	Rank
Makeshift materials (garbage, rubbish, waste paper)	2.46	0.78	3	3	1
Ignitable liquid	1.73	0.80	2	1	2
Paper, cardboard	1.58	0.67	1.5	1	3

[a]SD=Standard deviation

While the experts rejected the idea from the ISC DBT arson scenario that an accelerant and delay mechanism are important components of an adversary's IID, their conclusion that the attack is likely to occur along an architectural plane containing a window suggests that improved perimeter security would reduce the likelihood of a successful arson attack. The ISC DBT arson scenario was qualified by its creators that an arson attack would occur "outside the view of security countermeasures" (U.S. Department of Homeland Security, 2010b, p. 7.2.1). Additional research on the efficacy of perimeter security countermeasures may yield data recommending added protection from adversaries through enhanced human, visual, kinetic, or other technological security regimes.

D. FIRE EFFECTS MODELING APPLICATION

Fire is a dynamic phenomenon influenced by complex chemical, physical, and environmental factors. To study its effects under a variety of conditions without conducting full-scale destructive fire tests, fire research scientists and engineers have developed computerized mathematical fire models to simulate the effects of fire behavior in a virtual environment. According to Phillips (1995), "simulation models are widely used in science, engineering and mathematics in the study of problems that involve ordinary and partial differential *equations* (either overtly or implicitly)" (p. 5-1). In fire science and fire protection engineering, models can be used to simulate fire behavior, smoke migration, absorption of toxic products, human movement in response to threatening events, and the performance of fire protection systems.

Beyler and DiNenno (2003) reported that mathematical fire models could be classified as either probabilistic or deterministic. They found that

> probabilistic models attempt to deal with the random nature of fire behavior, whereas deterministic models presume that, given a well-defined physical situation, fire growth and behavior is entirely determined. Both approaches are valuable in understanding fire. (p. 3-70)

Within the deterministic framework, two major categories of fire models are recognized throughout the fire protection community. The first is known as a zone model, in which the room or compartment being modeled is divided into two regions or zones. The upper portion of the compartment is assumed to be filled with hot combustion gases, and the lower portion is presumed to be filled with relatively cooler air. Each of the upper and lower zones is assumed to have uniform temperatures and concentrations of various combustion gases. While this two-layer approach does not exactly mimic the complex environment of a burning room, zone models are desirable due to their reliability, relative simplicity, ease of use, and computational speed. The second major category of fire model is the computational fluid dynamic (CFD) method that relies on complex, three-dimensional computational cells. As Beyler and DiNenno explained, the room or compartment being modeled is computed as potentially thousands of discrete cells and the temperature, air velocity, and gas concentration of each cell is calculated. A CFD model can be used to represent the complexity of a hostile fire environment, yet greater computational capacity (processing power and random access memory) and more detailed data input is needed to create even simple models. A widely recognized deterministic CFD model (Fire Dynamics Simulator*)* was used in this study to represent conditions in the two prototypical environments.

Beyler and DiNenno (2003) advocated the use of deterministic methods and said that "perhaps the most important attribute of computer fire models is their ability to predict accurately and realistically the relevant fire behavior within their stated limitations" (p. 3-71). Despite their value, it is important to remember that fire models are only mathematical representations of dynamic physical and chemical events, and, as Phillips added, "simulation models can not [sic] ever be validated over the whole range

of their behavior" (p. 5-7). In other words, models cannot be viewed as an absolute representation or prediction of what might happen during a fire; they are intended to give competent professional scientists and engineers an additional evaluative tool to perform critical analysis of potential fire phenomena. Validation studies to assess FDS' accuracy at modeling pyrolysis and flame spread concluded that without "tuning" the pyrolysis rate coefficients, it was difficult to assess fire growth rates accurately in a combustible space (McGrattan, McDermott, Hostikka, & Floyd, 2010). While this conclusion does not invalidate the use of models, it is an acknowledgement that despite their robustness, they are not fully developed. Confidence in the models' reliability is enhanced if the mathematical relationships are established on sound scientific theory and full-scale experimentation and observation by knowledgeable people.

The Fire Dynamics Simulator (FDS) deterministic model developed and maintained by the U.S. Department of Commerce NIST was selected for the fire consequence analysis of the *Physical Security Criteria for Federal Facilities* standard and the DBT . It is a CFD model developed more than 25 years ago to solve complex mathematical equations[109] that represent the flow of heat and smoke from fires. The FDS allows the modeler to create a three-dimensional virtual environment that represents the space under study.[110] The modeler is able to specify spatial dimensions, construction materials, doors, windows, and other openings,[111] and specify the inclusion of fire protection systems, such as heat detection, smoke detection, or automatic sprinklers. The modeler also can create and position virtual objects inside the space, such as furniture. Data files collected from numerous small- and full-scale fire tests provide information on the thermal behavior and smoke generating characteristics of building materials (combustible or non-combustible) and furnishings.

[109] The calculations include Navier-Stokes equations that measure the movement of fluids and gases as they are affected by gravity, pressure and friction, direct numerical simulation for mathematically solving the Navier-Stokes equations and large eddy simulation to assess turbulence (Kandola, 1995; Ferziger, 1996).

[110] See *Fire Dynamics Simulator (Version 5) User's Guide* (McGrattan, McDermott, Hostikka, & Floyd, 2007) for a detailed explanation of the product.

[111] Described as "vents" in the model. The operation of vents affects the air flow to the fire.

The FDS enables the modeler to create a variety of fire scenarios using pyrolysis models for solid or liquid fuels, and place the ignition source and fuels anywhere in the virtual space. The model also can be configured to open or close vents at various points in the scenario to simulate the opening and closing of doors or windows that might occur during a live fire event, such as when occupants open a door to escape. In some scenarios, supply and exhaust fans—such as those occurring in heating, ventilating, and air conditioning or smoke management systems—can be simulated.

The FDS output files provide a wealth of information for assessing fire threats from the defined input parameters. The model is capable of providing data[112] on fire HRR, visibility obscuration caused by smoke development and migration, room temperatures, heat flows and thermal radiation, and incapacitating properties of toxic gases including carbon monoxide and carbon dioxide (as well as life threatening low oxygen concentrations). Jahn, Rein, and Torero (2008) reported that fire modeling tools provide good predictions of the thermal consequences of a fire, but their ability to predict fire development and HRR is problematic; therefore, the modeler must specify the HRR input variable. Results of the data runs can be produced in tabular or graphical outputs, or exported to another NIST computer program called *Smokeview* that can provide a two- or three-dimensional representation of the smoke, heated gases, and surface temperatures (Forney, 2010).

To perform the modeling routine, the FDS requires the creation of a computational domain that establishes the physical dimensions of the space, as well as any construction or furniture features that will affect the model's outputs. This virtual domain creates the boundaries for the model. According to McGrattan et al. (2007), it is the most challenging part of setting up the simulation because for both real and simulated fires, fire growth, and behavior is sensitive to the thermal properties of the environment, and even if all the material properties are known, the model itself may not be capable of rendering the fire with complete accuracy. Tables 47 and 48 in the two model test

[112] The model also can be run with a given HRR by inputting the information as a bounding condition.

environments provide the physical input criteria for the bounded domains. Material properties for building construction and interior finish, as well as automatic fire sprinkler characteristics, were developed from the FDS library databases.

The purpose for performing fire modeling in this study was to attempt to assess if one of the secondary research questions could be answered: "How can the arson threat scenario described in the DBT be quantified for the purposes of selecting permanent countermeasures?" Any fire behavior forecasts developed from the models must be considered blind predictions because the results are not compared to any experimental measures (Gissi, 2010). Virtual models of two prototypical federal properties were developed, 1) a single-story open office arrangement, and 2) a two-story public lobby and adjacent elevator shaft enclosures to represent a courthouse entrance. These examples were selected based on the fire incident data provide by the GSA that showed 80% of fires in GSA properties occurred in office buildings, and 10.9% (the second largest category) occurred in federal courthouses. Design fire scenarios were created by using the small quantity accelerant data from the Bureau of Alcohol, Tobacco, Firearms and Explosives. Design fire scenarios were run in both simulated environments to compare fire consequences and determine if recommendations to quantify elements of the DBT arson example could be accomplished.

1. Project Scope

In accordance with the SFPE *Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings*, the first step in performance-based analysis or design is to determine the project scope to describe the boundaries of the design. The office and courthouse lobby scenarios were selected based upon the predominant use of federal properties considered in this study.

a. Fire Model Test Environment 1: Single-Story Open Office Building

The first test example represents a single-story office building created to support typical administrative functions, such as public access, data collection, and

processing, bookkeeping, records management, or contract administration. The physical space consists of an open plan work area surrounded by individual offices. The building consists of non-combustible construction, and is protected by a wet pipe automatic sprinkler system. (See Figure 10 for a graphical representation of the space). Support functions, such as restrooms, closets, and a breakroom/kitchenette, are included. The non-combustible construction and the fire sprinkler system can be considered the integral elements of the permanent countermeasures for this scenario's evaluation. A perimeter office with an exterior window and near the rear exit is used as the room of fire origin.

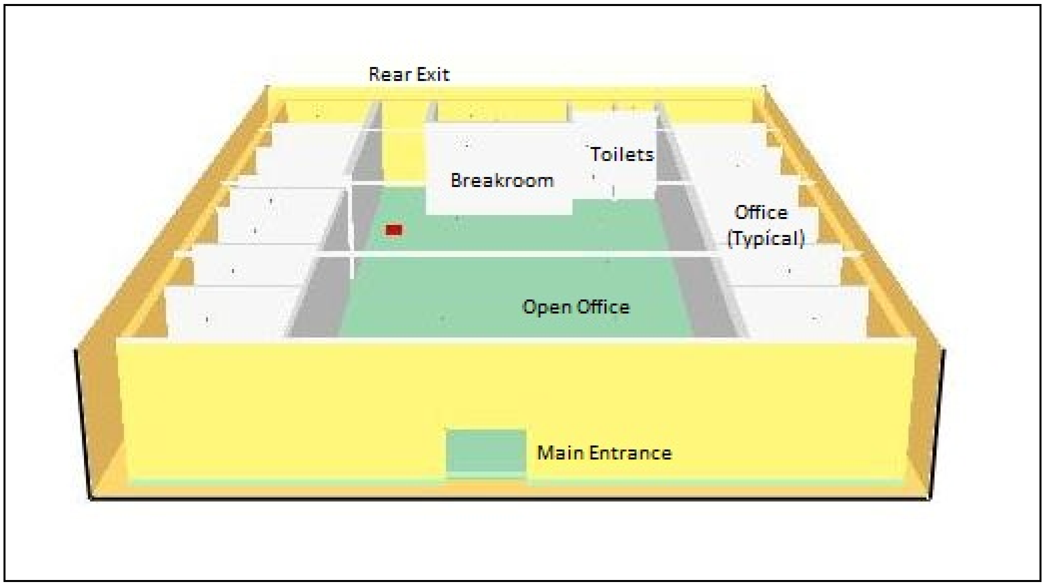

Figure 10. Fire Model Test Environment 1: Single-Story Open Office Building

To represent the fuel package in the small office and maintain simplicity in the modeling, the contents of the small office were rendered as a single object (upholstered sofa) having the material properties of polymethyl methacrylate (PMMA) and a mass equal to the accumulation of combustibles found in a typical office. PMMA's material properties[113] have been studied extensively in laboratory-environment live fire research, and are a material commonly used to represent the fuel package in modeling scenarios. The modeled object's mass (1305 lbs/592 kg) was predicated on

[113] Conductivity, specific heat, density, and emissivity.

Madrzykowski's (1996) full- and bench-scale fire research conducted on office work stations. Madrzykowski surveyed the GSA Central Office in Washington, D.C. to create the typical cubicle fire load for his HRR study. Having a single object as the ignition target from the already ignited accelerant lessened the number of furnishing obstructions modeled.

Table 47. Fire Model Test Environment 1: Single-Story Open Office Physical Input Criteria

	Condition/Material	**U.S. Customary Units**	**SI Units**
Room dimensions	--	11.5 x 12 ft	3.5 x 3.67 m
Room Area	--	138 ft^2	12.5 m^2
Floor height	--	0 ft	0 m
Ceiling height		12 feet	3.6 m
Model dimensions	--	19.6 x 22.9 x 20.5 ft	6 x 7 x 6.2484 m
Ceiling configuration	Smooth, flat	--	--
Ceiling finish	Mineral fiber lay-in ceiling tile	5/8-inch	16 mm
Ambient temperature	--	68 °F	20 °C
Ambient relative humidity	--	40%	40%
Ambient barometric pressure	--	760 mm Hg	101 325 Pa
Automatic sprinklers	Wet pipe	--	--
	Quick Response Sprinklers: Response Time Index	165	165

	Condition/Material	U.S. Customary Units	SI Units
	Sprinkler discharge density	0.10 gpm/ft^2	139 Lpm/m^2
	Operating temperature	165 °F	74 °C
	Sprinkler discharge density	0.10 gpm/ft^2	139 Lpm/ m^2
	Sprinkler K Factor	5.6	80
	Sprinkler flow	18 gpm	68.1 lpm
Floor covering	Nylon carpet	9/32-inch	7.8 mm
	Bonded urethane pad	3/8-inch	9.5 mm
Subfloor	Concrete slab	6-inch	150 mm
Wall material	Gypsum wallboard on steel framing	5/8-inch	16 mm
Vents	Exterior window (open)	32 ft^2	3 m^2
	Interior door (open)	24 ft^2	2.23 m^2
Smoke management	None	--	--
HVAC	No shutdown	0.12 ft^3/ft^2	.003 m^3/0.093 m^2

The FDS provides results that can be captured in a spreadsheet for graphic representation in charts and displayed virtually using *Smokeview*. Figure 11 is an isometric rendering of design fire's area of origin in the small office environment.

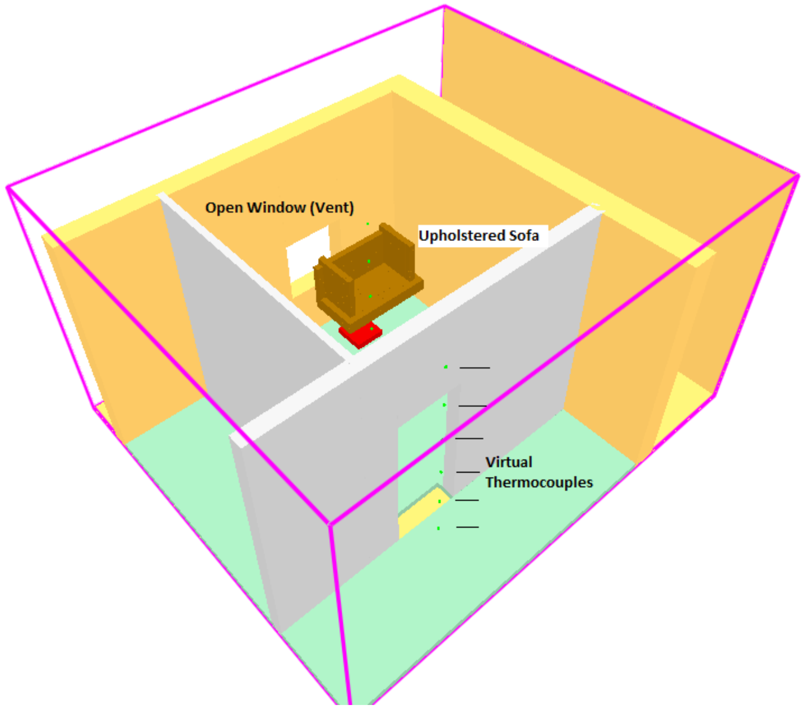

Figure 11. Isometric Rendering of Fire Model Test Environment 1 Area of Origin

In the rendering, note that the exterior window is labeled “open” to represent an unrestricted vent to the atmosphere based on the broken window conditions of the design fire scenario. The upholstered sofa represents the entire fuel package in the room. The square beneath the upholstered sofa is the device that contains the accelerant, modeled as a 1 MW burner. Small dots inside and outside the room represent two virtual thermocouple threes with thermocouples distributed in 24-inch (61 cm) increments between the floor and ceiling. The virtual thermocouple tree in the office is centered in the room; the virtual thermocouple tree outside the room is 12 inches (30 cm) from the vertical plane of the door.

During its run time, *Smokeview* can represent dramatically the speed with which life-sustaining conditions are threatened during a fire. Figure 12 illustrates the fire and smoke conditions in the small office only 79.2 seconds after ignition. The analysis of smoke obscuration on egress behavior conducted by Chu et al. (n.d.) described how

quickly building occupants must respond to achieve RSET; *Smokeview's* rendering of the speed associated with these deteriorating conditions may convince skeptics of the importance of rapid egress.

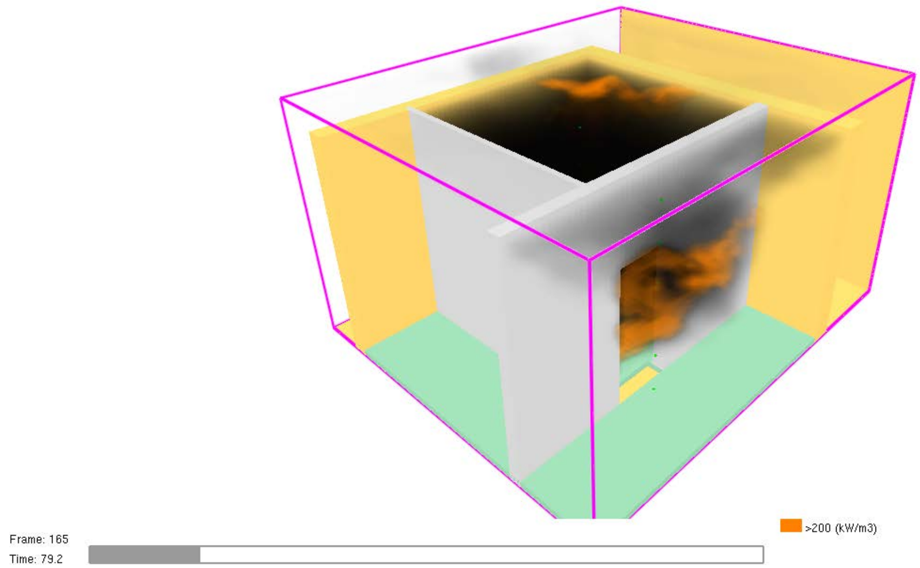

Figure 12. Representative *Smokeview* Smoke and Fire Conditions

Smokeview also has the capability of rendering temperature variations in planar sections called slice files. The color palette represents different room temperatures at that point in the event ranging from blue (ambient) to red that signifies the highest temperatures achieved in the modeled environment. Figure 13 represents a temperature slice file taken at approximately four minutes (247.7 seconds) after ignition in the office that was not protected by automatic sprinklers. The turbulent fire gases at the room's ceiling reach approximately 1,652°F (900°C), while the temperatures in the adjacent open office space range from ambient (68°F or 20°C) to about 200°F (95°C).

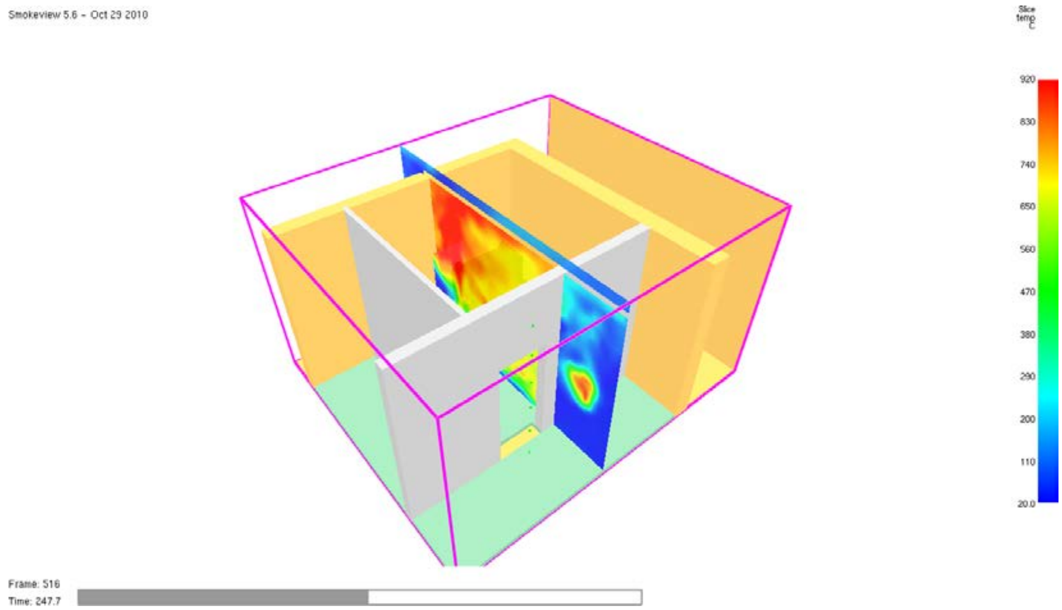

Figure 13. Representative *Smokeview* Slice File in Small Office Model

Finally, when displaying renderings of test environments in which fire sprinkler systems are included in the model, *Smokeview* simultaneously can display virtual water droplets that represent sprinkler water discharge. Figure 14 displays this feature representing sprinkler operation inside the office and adjacent open space about 1¼ minutes (75.4 seconds) after ignition.

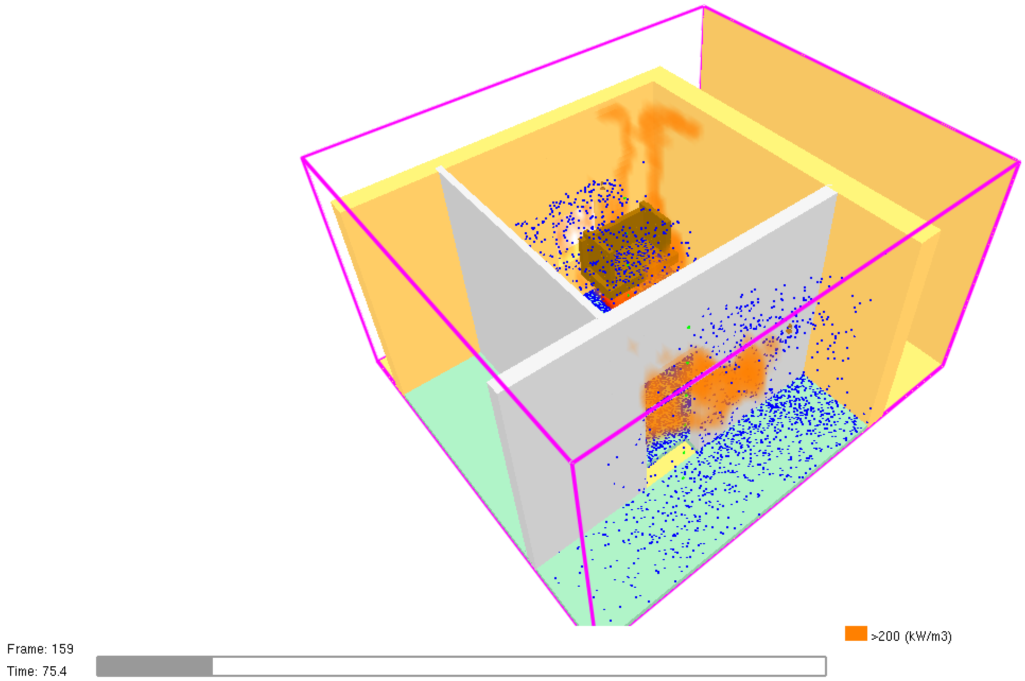

Figure 14. Representative *Smokeview* Fire Sprinkler Virtual Water Droplets in Small Office Model

b. Fire Model Test Environment 2: Two-Story Courthouse Lobby

The second test example represents a portion of an unspecified-size federal courthouse, and consists of the public entrance into a two-story open lobby area on the first floor. (See Figure 15 for a graphical representation of the space). The lobby is adjacent and open to a large, undefined space outside the boundary of the model's domain but influences the model as a vent, which in the FDS can be a large, unobstructed opening that allows the free exchange of entrained air and escape of combustion products. This large vent is identified by the two shaded areas marked "open beyond" in the vertical plane of the graphic. The two-story lobby includes two banks of elevators each having two cars in two independent shafts. The lobby contains a security station, assorted pieces of upholstered furniture, and an information kiosk. The overall building consists of fire resistive construction, and is protected by a wet pipe automatic sprinkler system. The fire-resistive construction and the fire sprinkler system can be considered the integral elements of the permanent countermeasures for this scenario's evaluation. (Note

that the security station and information kiosk do not appear in this rendering; the composition and mass of the furniture is included in the model inputs in Table 48).

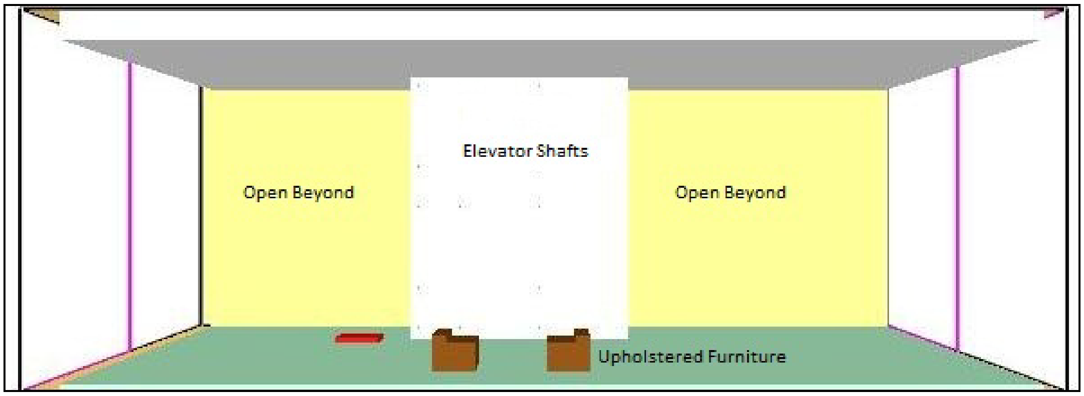

Figure 15. Fire Model Test Environment 2: Two-Story Courthouse Lobby

Like the rendering of the small office fire model test environment, the larger space is displayed by *Smokeview* in an image the enables the viewer a closer look at the pre-event conditions. Figure 16 shows the design fire model at 60 seconds after ignition, and includes the virtual water droplets from the fire sprinkler system. This rendering includes smoke (soot) outputs.

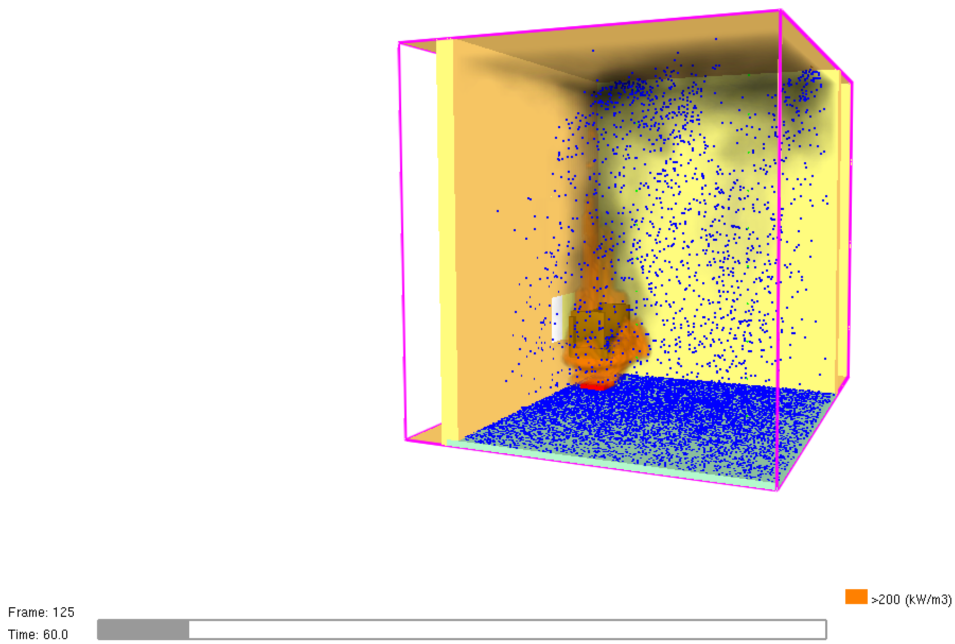

Figure 16. Representative *Smokeview* Fire Sprinkler Virtual Water Droplets in Courthouse Lobby Model

Table 48 provides the physical input criteria for the bounded domains used in the FDS model run.

Table 48. Fire Model Test Environment 2: Two-Story Courthouse Lobby Physical Input Criteria

	Condition/Material	U.S. Customary Units	SI Units
Room dimensions	--	48 x 50 ft	14.6 x 15.2 m
Area	--	2400 ft^2	222 m^2
Floor height	--	0 ft	0 m
Ceiling height	--	20 feet	6.1 m
Model dimensions	--	19.6 x 22.9 x 20.5 ft	6 x 7 x 6.2484 m
Ceiling configuration	Smooth, flat	--	--
Ceiling finish	Tectum[a] (direct-attached)	1.5 in	38.1 mm
Ambient temperature	--	68 °F	20 °C

	Condition/Material	U.S. Customary Units	SI Units
Relative humidity	--	40%	40%
Barometric pressure	--	760 mm Hg	101 325 Pa
Automatic sprinklers	Wet pipe	--	--
	Quick Response Sprinklers: Response Time Index	165	165
	Operating temperature	165 °F	74 °C
	Sprinkler discharge density	0.10 gpm/ft^2	139 Lpm/ m^2
	Sprinkler K Factor	5.6	80
	Sprinkler flow	18 gpm	68.1 lpm
Floor covering	Granite	--	--
Wall material	Granite	--	--
Vents	Exterior window (open)	32 ft^2	3 m^2
	Adjacent open space		
Smoke management	None	--	--
HVAC	No shutdown	0.12 ft^3/ft^2	.003 m^3/0.093 m^2
Elevator recall	Phase One[114] on lobby smoke detection		

[a]Trade name for a wood-fiber composite panel.

The *Smokeview* visual representations, when combined with expert analysis of data outputs generated by the FDS, can be used by Facility Safety Committee members to evaluate the effectiveness of proposed permanent countermeasures against arson threats when the input data is accurately represented.

114 Elevator cars are returned to designated floor of egress. Smoke detection devices are located in the elevator lobbies, elevator hoistway (shaft), and elevator machine room (ASME, 2010).

2. Project Goals, Design Objectives and Performance Criteria

The second step in the *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings* is the establishment of fire safety goals that normally are prescribed by the project stakeholders. The goals are generic statements addressing desirable outcomes, such as protecting life or property, providing for continuity of operations, or limiting environmental impacts of the fire (National Fire Protection Association & Society of Fire Protection Engineers, 2000). For the purpose of this thesis, the goals of protecting human life (occupants and visitors), and maintaining the organization's on-going operational capability in accordance with federal continuity of operations requirements, were selected as the most appropriate goals for the sample scenarios.

Eventually, the goals are refined into more specific design objectives and framed in engineering terms so they can be measured. For office-type scenarios, federal regulations describe these three performance objectives in a building protected by automatic fire sprinklers: 1) prevent flashover in the room of fire origin, 2) limit fire size to no more than 950 Btu/sec (1 MW or 1000 kW), and 3) prevent flames from leaving the room of origin (41 CFR 102-80.115, 2005). In running the fire modeling routine, the demarcated times from ignition to sprinkler operation, the fire reaching 950 Btu/sec (1 MW or 1000 kW), or flames leaving the room of origin, are critical. The shortest of the three times is the allowable time available for escape permitted by the federal fire safety regulations when calculating the safety margin between ASET and the RSET (41 CFR 102-80.115, 2005). Although it is recognized that a fire in the perimeter office may threaten the remainder of the office and impede egress during normal business hours, separate egress modeling analyses were not conducted because representative population data could not be obtained.

3. Design Fire Scenarios

Design fire scenarios are those events that the design team determines to be plausible based on an analysis of the property, its use and contents, nature of the occupants, and risk. To test the hypothesis whether performance-based fire protection

design methods are suitable to evaluate the effectiveness of the *Physical Security Criteria for Federal Facilities* permanent countermeasures, the data collected in the Delphi survey was used to create the modeling framework described in these scenarios. According to the Delphi results, the most likely arson scenario in a federal building or facility would be "an adversary breaks a window and ignites burnable materials (make shift materials: garbage, rubbish, waste paper), that can be reached inside." To complicate the scenario, a 1,000 kW (1MW) burner representing a flammable liquid IID was included as a model input. Figure 17 represents the heat release rate signature of the IID. The models were run both with and without the operation of the automatic fire sprinkler systems specified in the model inputs (Tables 47 and 48). The automatic sprinkler systems characterize the permanent countermeasures being evaluated.

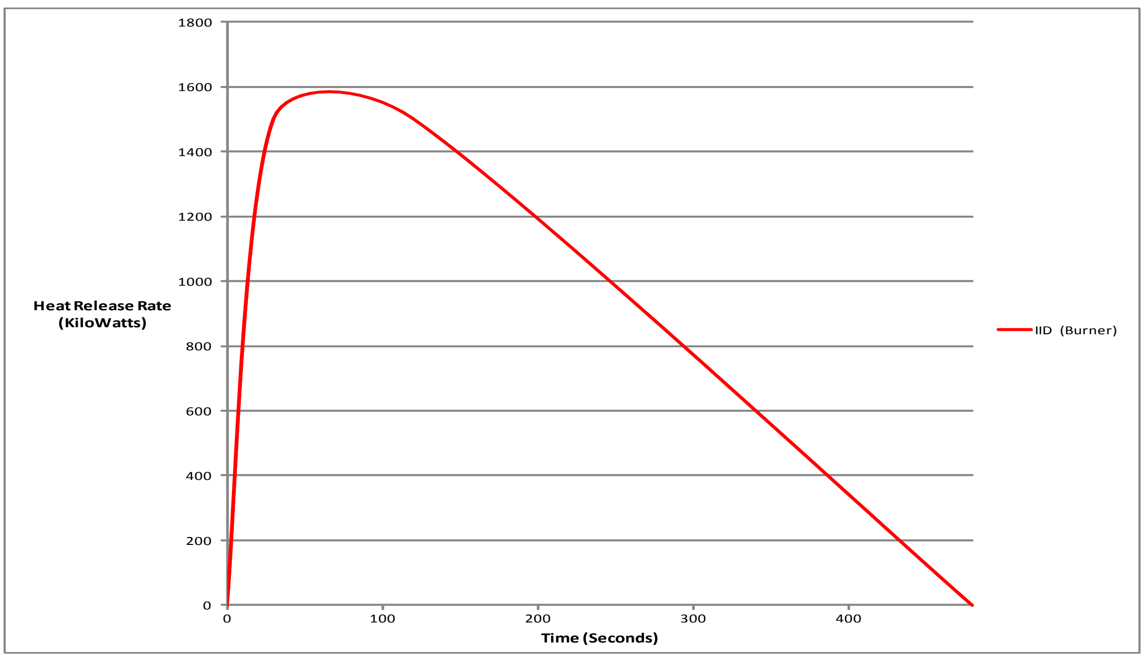

Figure 17. HRR Signature of Improvised Incendiary Device

4. Pass-Fail Criteria

The design fire scenarios were employed not to test the performance of any hypothetical or real designs, but to determine if quantifying the character of a fire could

aid in evaluating the range of permanent countermeasures. Consequently, simple pass-fail criteria were established to assess the results of the design fire model runs. Given that federal regulations specify three performance objectives in a building protected by automatic fire sprinklers, any of the following results qualified as a successful model outcome: 1) prevent flashover in the room of fire origin, 2) limit fire size (HRR) to no more than 950 Btu/sec (1 MW or 1000 kW), and 3) prevent flames from leaving the room of origin (41 CFR 102-80.115, 2005). For the purposes of evaluation, flashover was defined as a temperature of 1,112°F (600°C) (Drysdale, 2002, p. 306) at six inches (152 mm) below the ceiling. Establishing whether flames leave the room of origin is problematic in the virtual environment because of the subjective interpretation of what constitutes "flames." Flames are a mixture of fire gases and soot particles that emit visible and infrared light. Depending upon where they are observed in a room fire—and what part of the flame is being evaluated—their temperatures may range from 1,652°F (900°C) in what is called the continuous flame region to about 608°F (320°C) at the flame tip (McCaffrey, as cited in Babrauskas, 2006). The FDS does not measure flame temperature. Therefore, the ability through modeling to assess whether flames leave the room of origin is susceptible to subjective interpretation. To establish if or when flames left the room of origin, flame temperature was defined as visual products of combustion transported by fire gases at 1,500°F (815°C), and was measured by a single virtual thermocouple tree located in the open portion of the office building adjacent to the rear path of egress, and in the open areas behind the elevator shafts in the two-story courthouse lobby.

5. Results

To display some of the data sets available to Facility Safety Committee members who might employ the FDS and *Smokeview* as decision-guiding tools in their evaluation of proposed permanent countermeasures, the models were run with the test environments represented both as protected by automatic fire sprinklers and without sprinkler protection. No first order analysis was performed; all data results were obtained from the FDS based on the criteria provided in Tables 47 and 48. The second condition (no

sprinklers) represents circumstances in which sprinklers may be absent from the building design and construction, or they have been disabled through carelessness or malicious action, such as might occur if an adversary were trying to destroy a building by fire.

It must be emphasized that the results presented in this paper are based on mathematical models only, and may not represent actual fire conditions or behavior. Any mathematical analysis includes an amount of uncertainty, as well as expert analysis and interpretation of the results.

a. Fire Model Test Environment 1: Single-Story Open Office Building

Results from Fire Model Test Environment 1, the single story open office building, are portrayed below. One of three performance objectives mandated under federal fire safety regulations (41 CFR 102-80.115, 2005) is that flashover in sprinklered buildings must be prevented in the room of origin. For this thesis and the fire models, flashover was defined as a temperature of 1,112°F (600°C) at 6 inches (152 mm) below the ceiling. Figures 18 and 19 display the temperature outputs in two-foot (610 mm) increments inside the small office. In the office protected by quick response automatic sprinklers (operating temperature 165°F [74°C]), the temperature spikes to about 527°F (275°C) within the first 30–35 seconds until the sprinkler operates and begin to dramatically cool the atmosphere between three and 11 feet (914 to 3,352 mm) above the floor. After the first minute, the temperature in that zone remains between 122 and 302°F (50–150°C).

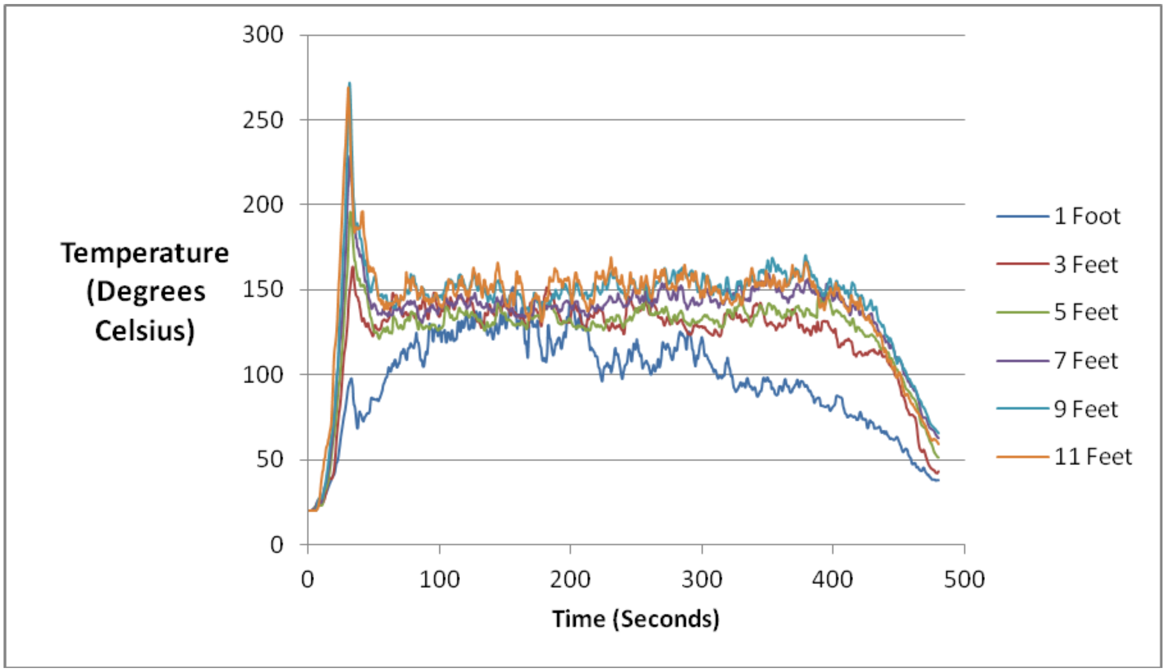

Figure 18. Small Office Temperature Curves with Sprinklers

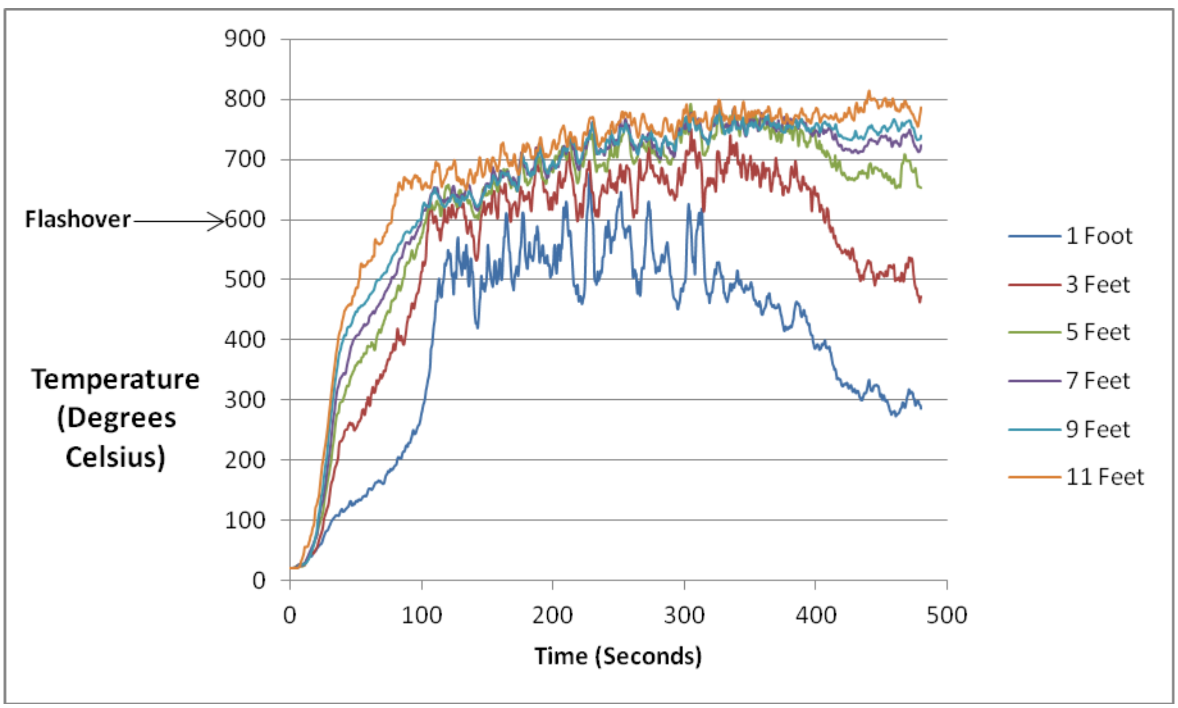

Figure 19. Small Office Temperature Curves without Sprinklers

According to the data presented in Figure 18, flashover is never achieved in the office space protected by automatic sprinklers; whereas without sprinkler protection, flashover at six inches (152 mm) below the ceiling is reached between 50 and 100 seconds (approximately 80 seconds) after ignition (Figure 19). The temperature in the non-sprinklered space continues to rise to about 1,472°F (800°C) within six inches of the ceiling, and anywhere from 572 to 1,472°F (300 to 800°C) throughout the entire habitable space.

These conditions are visually rendered in Figures 20 and 21, which are slice files captured 330.7 and 326.4 seconds after ignition with corresponding temperature ranges, respectively.[115] In both cases, even if a reviewer were unable to interpret the scientific data, the emotional responses to the represented color spectrum suggest areas within the space ranging from tolerable to dangerous to human occupancy (Valdez & Mehrabian, 1994). The blue end of the spectrum represents survivable temperatures from 68 to 131°F (20 to 55°C) where the orange-red end of the spectrum represents temperatures from 572 to almost 1,700°F (335 to 920°C) that could not support human life in a normal office environment.

[115] Note the open vent at the left side midpoint of the illustrations in both Figures 19 and 20. This vent represents the adversary's access point—by breaking the window—that provides both additional air for combustion and a path for the fire.

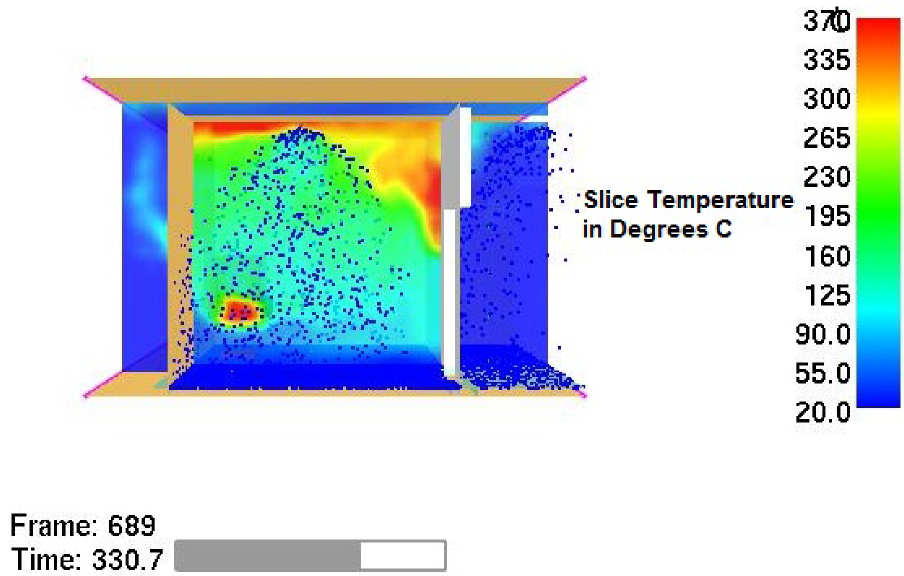

Figure 20. Temperature Slice File in Sprinklered Small Office

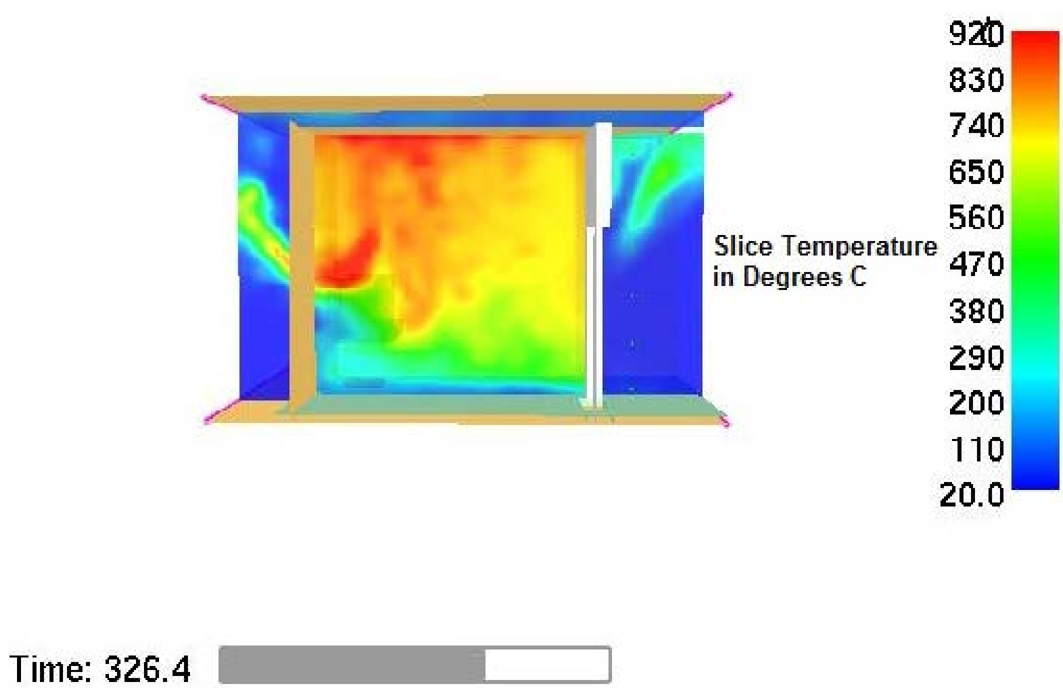

Figure 21. Temperature Slice File in Non-sprinklered Small Office

The second criterion needed to satisfy federal building safety regulations is that the fire size is limited to no more than 950 Btu/sec (1 MW or 1,000 kW). Figures 22 and 23 represent the fire size in terms of HRR that describe the amount of heat released over a unit of time by one or more burning objects (See Table 22).

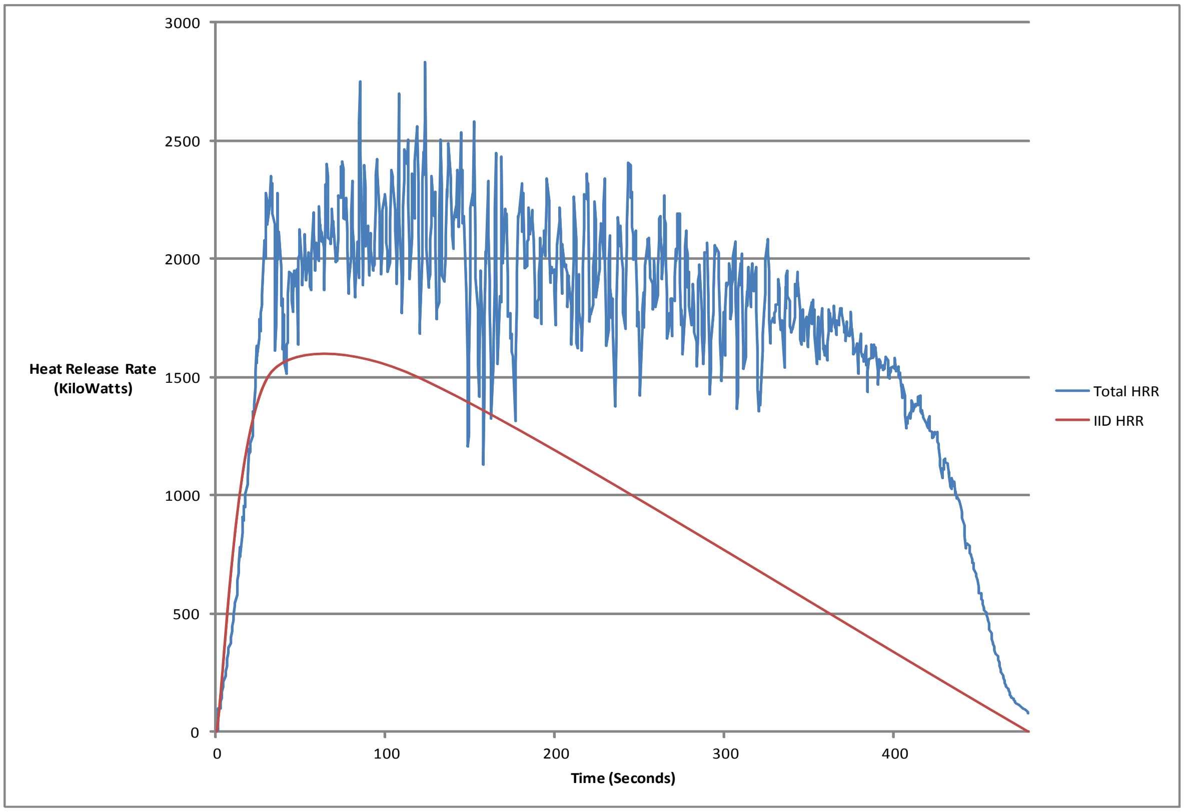

Figure 22. Sprinklered Small Office HRR

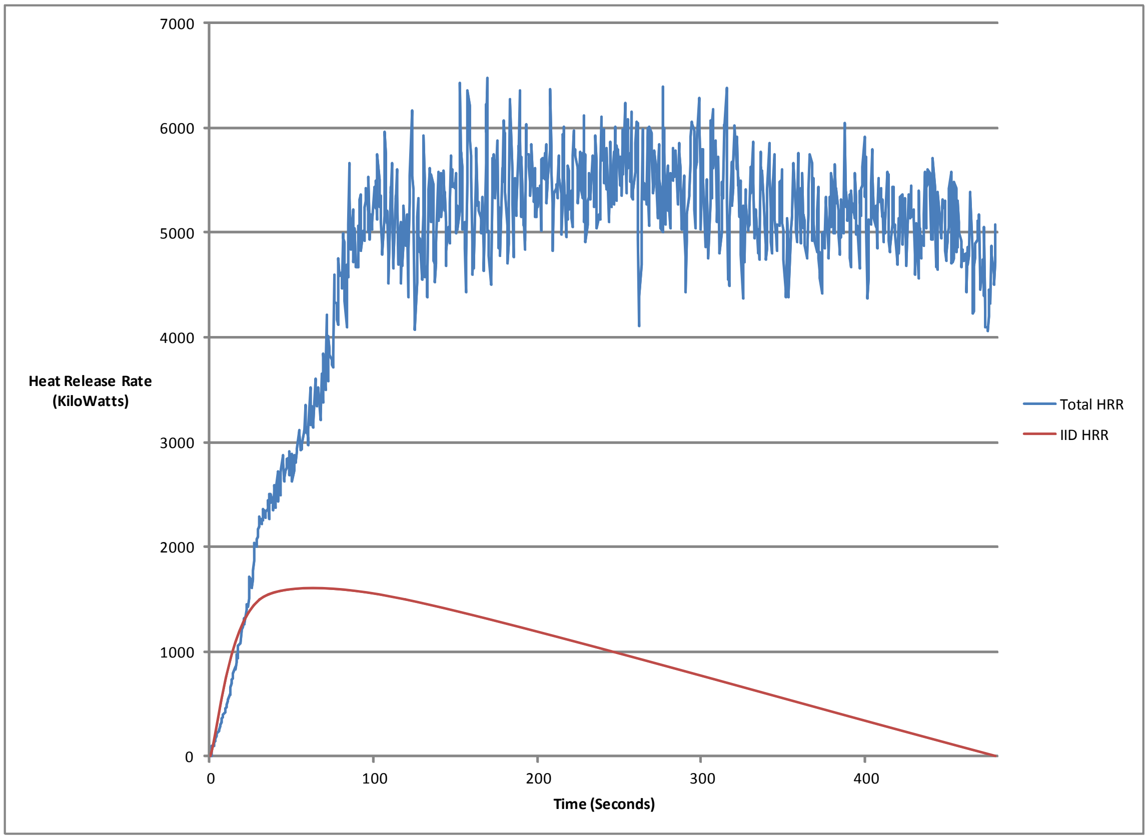

Figure 23. Non-sprinklered Small Office HRR

In both scenarios, the virtual fires exhibit rapid growth, and exceed the 950 Btu/sec (1,000 kW or 1 MW) limit in less than 30 seconds. This behavior is consistent with the ultrafast T^2 HRR curve shown in Figure 8 and can be employed as an important constituent in setting the design fire criteria used to analyze performance-based design solutions. As Figure 22 shows, except for several anomalous spikes between 100 and 120 seconds, the peak HRR occurs at about 2,370 Btu/sec (2,500 kW or 2.5 MW) at 120 seconds and begins a steady downward trend as the operating sprinklers control the fire toward extinction. This HRR represents the energy released by the IID and the furnishings and other combustibles in the space, as well as the re-radiative influence of the enclosure. The fire drops below the 950 Btu/sec (1 MW or 1,000 kW) threshold at about 420 seconds (7 minutes) after ignition. The HRR curve corresponds to the IID HRR curve such that an approximately 950 Btu/sec (1,000 kW or 1 MW) difference occurs between the two at any point within the federal criteria.

However, in the non-sprinklered space, the peak HRR is about 5,686 Btu/sec (6,000 kW or 6.0 MW) at about 120 seconds, and trends downward only slightly during the remainder of the model run (an additional 360 seconds or six minutes), which suggests the small office remains a highly energized environment throughout the duration of the incident due to the amount of fuel and re-radiative effects of the enclosure. The absence of automatic sprinkler protection renders this space untenable, and a failure to meet the federal fire safety criteria.

Finally, the federally mandated third performance objective for fire protection in office occupancies is to confine the flames to the room of origin. For this scenario, a flame temperature was defined as visual products of combustion transported by fire gases at 1,500°F (815°C), and was estimated by a single virtual thermocouple tree located in the open office space outside the small office defined as the room of fire origin.

Figures 24 and 25 represent the temperature ratings at 24-inch (610 mm) intervals 12 inches (30 cm) outside the small office. In neither case (sprinklered or non-sprinklered) did the flame temperature outside the office exceed the 1,500°F (815°C) performance threshold.

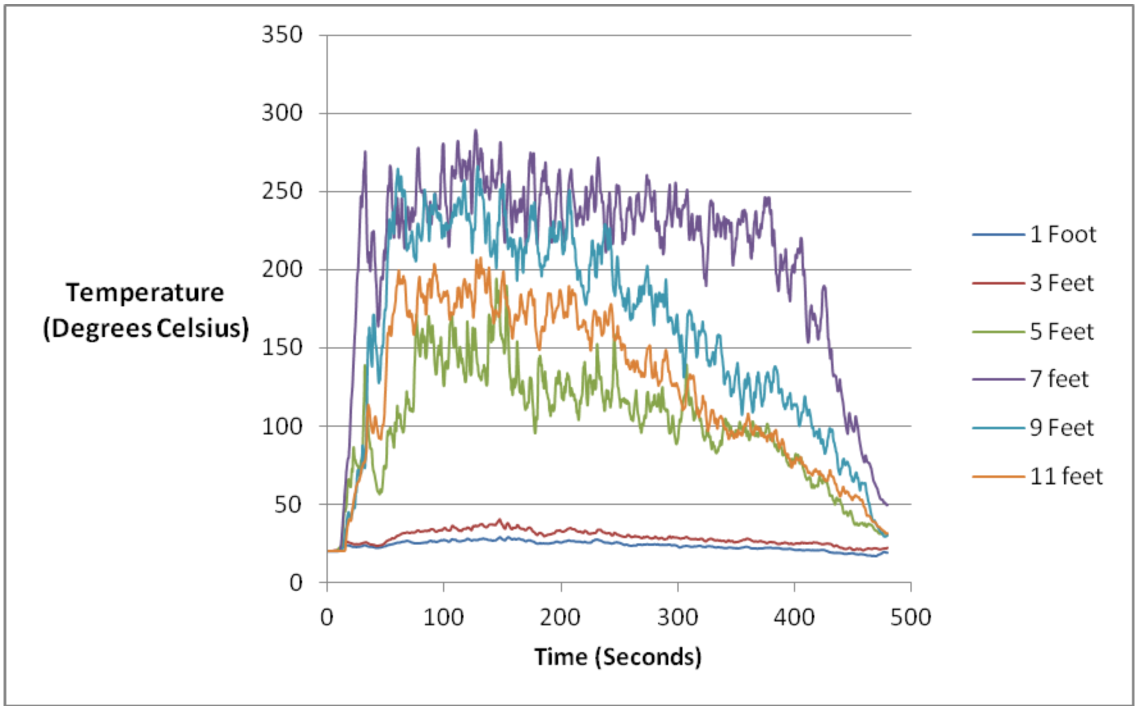

Figure 24. Flame Temperature Outside Small Office Room of Origin (Sprinklered)

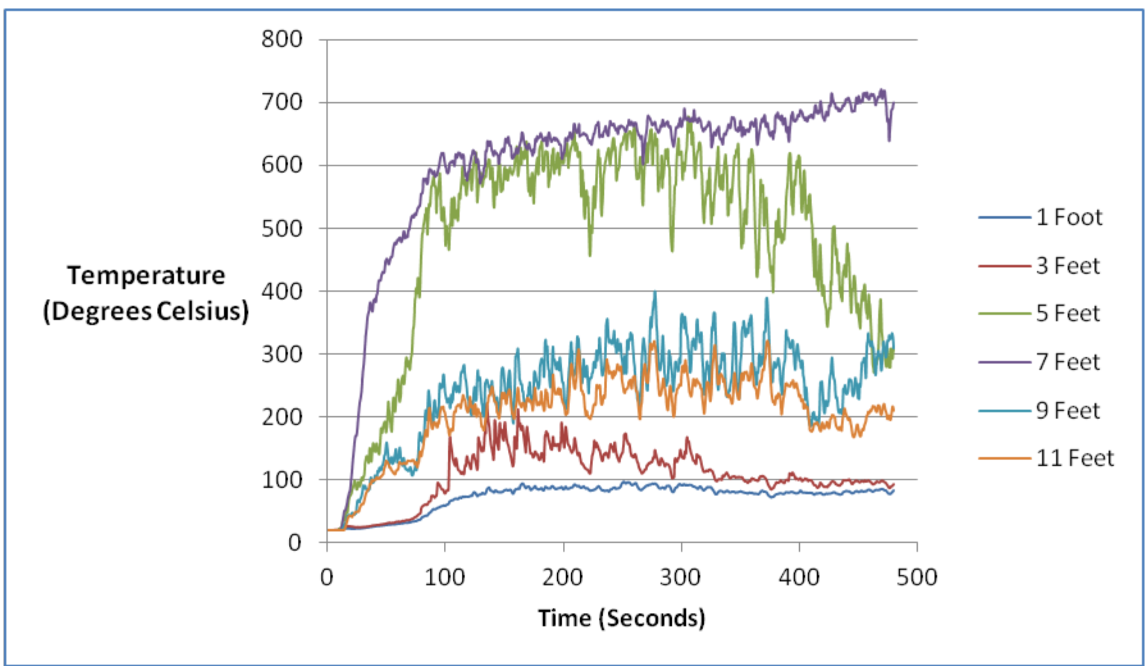

Figure 25. Flame Temperature Outside Small Office Room of Origin (Non-sprinklered)

Data points in Figure 25 demonstrate what appears to be an anomaly, temperatures at 5 and 7 feet above the floor (1,524 and 2,134 mm) are higher than those at nine or 11 feet (2,743 or 3,533 mm). Normally, higher fire temperatures are recorded at the highest point of an enclosure in which the thermal plume reaches the ceiling. The apparent discrepancy can be explained by the design of the wall between the small office and the open area, and position of the virtual thermocouples. Notice in Figures 13 and 21, the wall where the office door occurs is designed with a lintel approximately 5 feet (1,524 mm) down from the ceiling that provides a solid barrier between the small office and open area. This lintel limits the flaming ceiling jet and turbulent outflow in the small office from escaping into the open area. The doorway (a vent) between the two spaces is located beneath the lintel, and allows flames to escape the room of origin at the 5 to 7 foot range (1,524 and 2,134 mm) where they are detected by the virtual thermocouples.

b. Fire Model Test Environment 2: Two-Story Courthouse Lobby

The second test environment represents a portion of an unspecified-size federal courthouse, and consists of the public entrance into a two-story open lobby area on the first floor. (See Figure 15 for a graphical representation of the space). The model was subjected to the same design fire test stress as the small office building. Figures 26 and 27 represent the temperatures at different elevations for a lobby protected by automatic fire sprinklers and one that is not, respectively. In Figure 26, the temperature near the second-floor ceiling at 19 feet (5,791 mm) above the floor ranges between 248 to 320°F (120 to 160°C) whereas the temperature range at the walking surface range from 68 to 140°F (20 to 60°C). In the non-sprinklered lobby (Figure 27), the ceiling temperature nearly reaches flashover (spiking at 932°F [500°C] at about 120 seconds), while after 60 seconds, the walking surface temperatures remain dangerously high 212 to 257°F (100 to 125°C).

In neither case did the design fire reach the critical flashover temperature of 1,112°F (600°C) at six inches (152 mm) below the ceiling. Therefore, this design can be interpreted as meeting one of the three fire safety criteria codified in federal law.

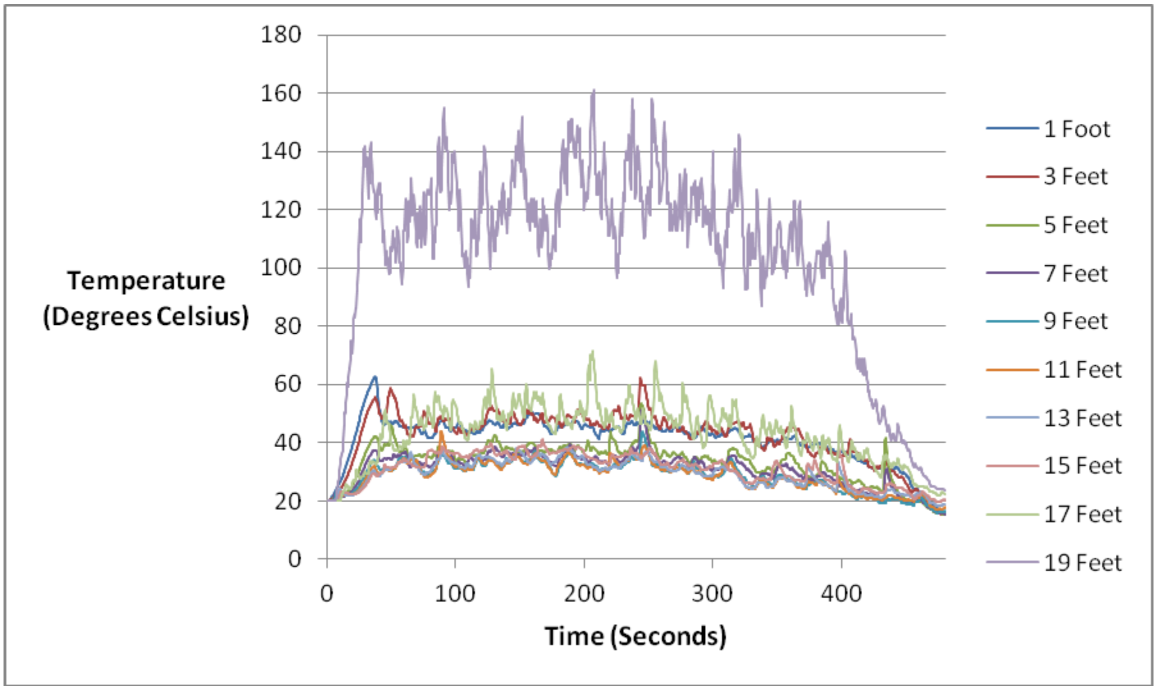

Figure 26. Courthouse Lobby Temperature Curves with Sprinklers

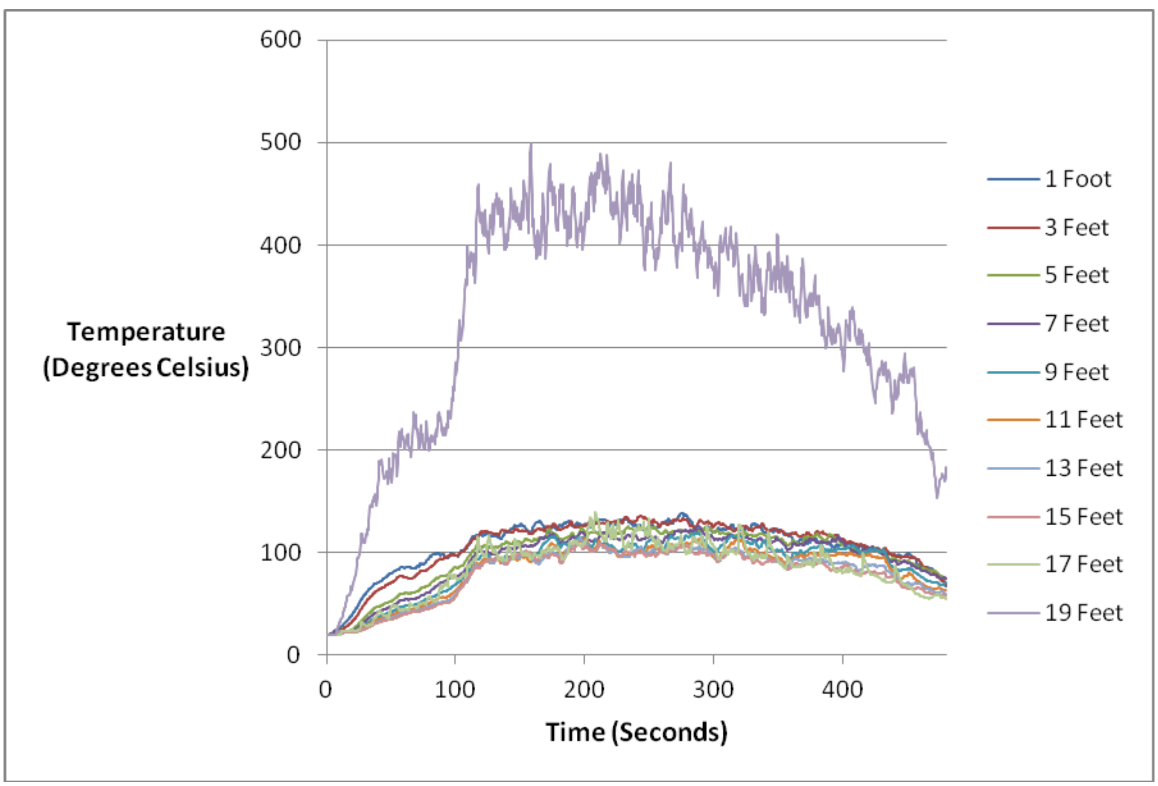

Figure 27. Courthouse Lobby Temperature Curves without Sprinklers

Figures 28 and 29 are slice files of the virtual courthouse lobby at 326.4 and 331.2 seconds after ignition, respectively. While both images evoke an emotional response that suggests the environment might easily support human life, it is important to note the difference in temperature scale at the right hand side of the illustration. The color spectrum in Figure 28 (the sprinklered lobby) ranges from 59 to 599°F (15 to 315°C), while the temperatures in Figure 29 range from 68 to 1,148°F (20 to 620°C). A FSC reviewing modeling data should insist that data be represented consistently in a fashion that permits balanced analysis.

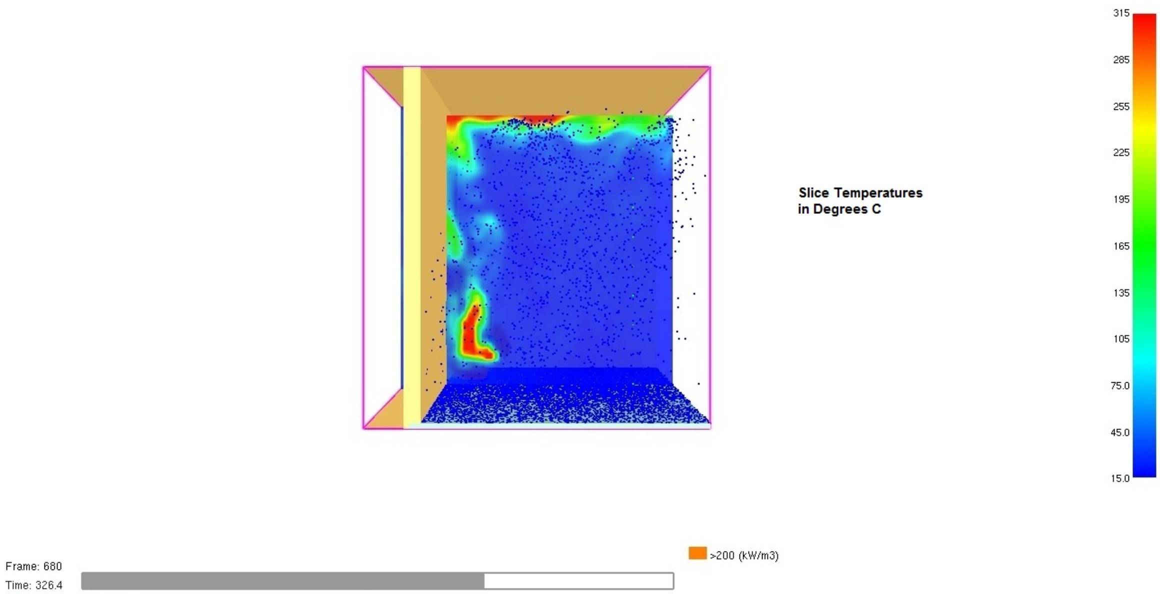

Figure 28. Temperature Slice File in Sprinklered Courthouse Lobby

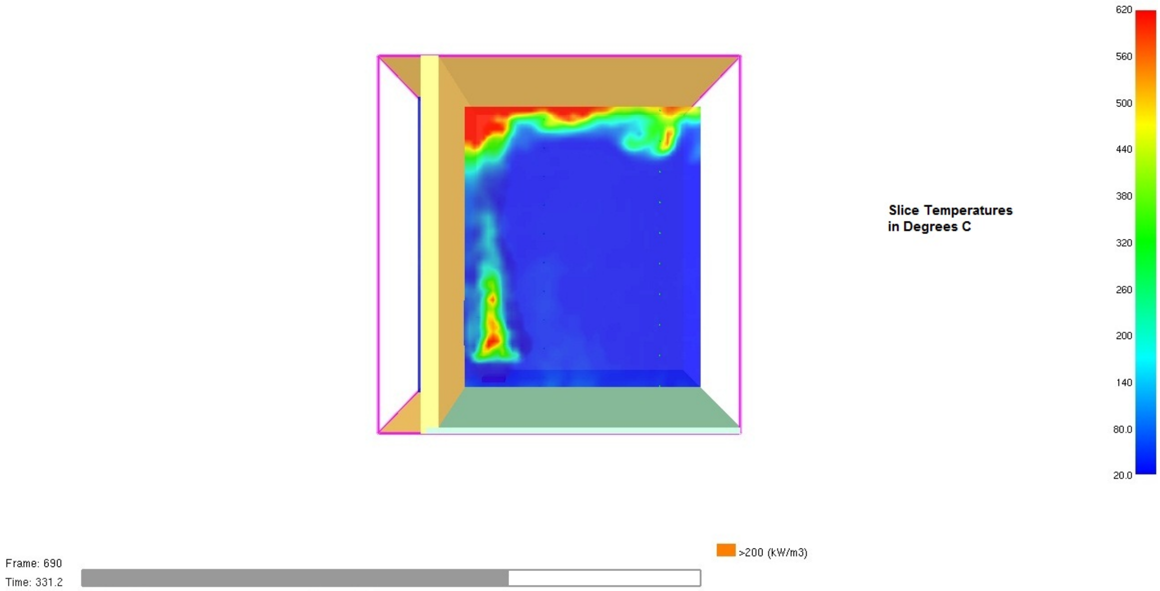

Figure 29. Temperature Slice File in Non-sprinklered Courthouse Lobby

The second performance objective in federal fire safety criteria (the HRR not exceeding 950 Btu/sec [1 MW or 1,000 kW]) is surpassed in less than 30 seconds in both the sprinklered and non-sprinklered scenarios (Figures 30 and 31, respectively). This behavior is consistent with the ultrafast t^2 HRR curve shown in Figure 8 and is an important constituent in setting the criteria to analyze performance-based design solutions. For the most part, the sprinkler system cools the environment and keeps the total HRR within 950 Btu/sec (1,000 kW or 1 MW) of the IID HRR curve. However, between 100 and 200 seconds, HRR values exceed this difference. Those data simply may be the result of sensitivity issues in the modeling. According to McGrattan (2007), the FDS may produce results having a difference of as much as 15% above or below actual HRR. For the purpose of this thesis, with the limited number of model runs and the fact a period exists in which the total HRR exceeds the performance threshold, it must be concluded that is uncertain whether the sprinkler system is an effective countermeasure. Consequently, this specific scenario needs additional study and analysis.

Figure 31, the non-sprinklered lobby space, shows the total HRR that exceeds the permitted threshold by 1,900 Btu/sec (2 MW or 2,000 kW) or more, which thus, does not comply with federal fire safety criteria.

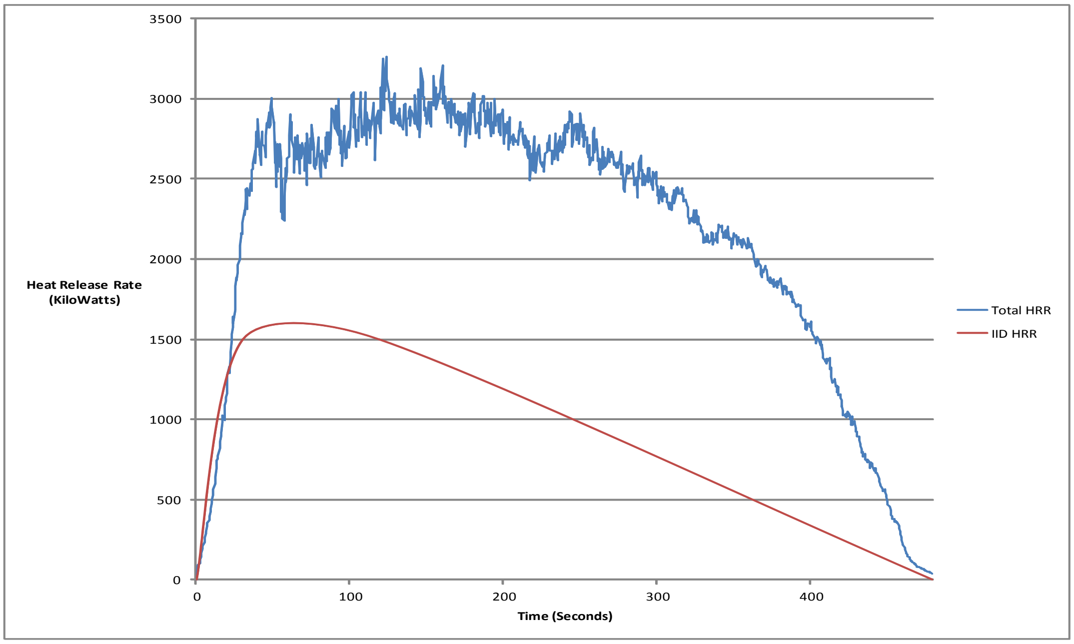

Figure 30. Sprinklered Courthouse Lobby HRR

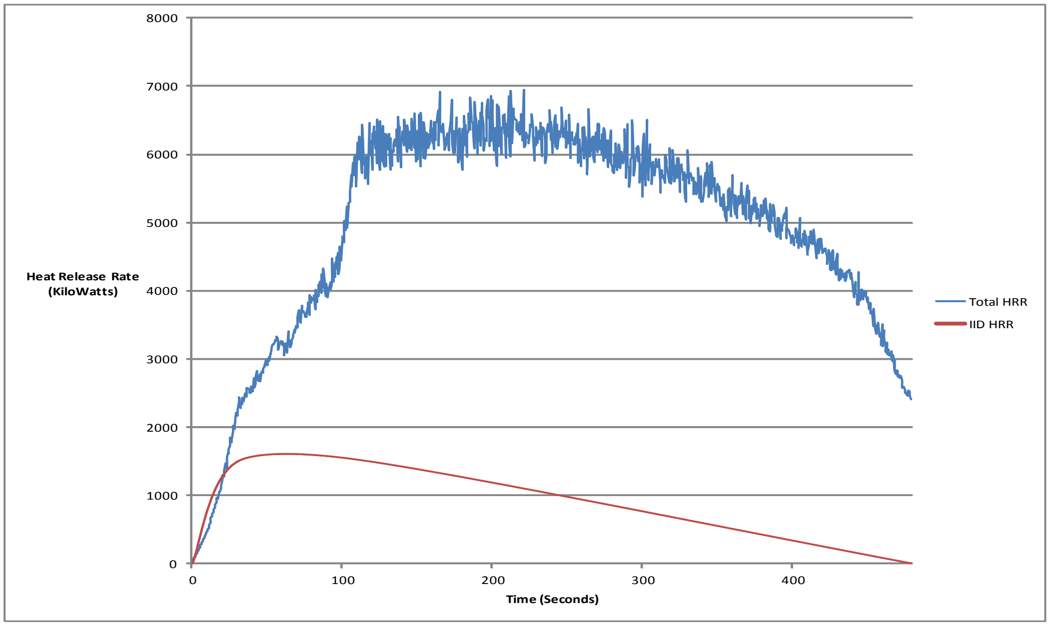

Figure 31. Non-sprinklered Courthouse Lobby HRR

The final scenario modeled in this environment was to determine whether the flames left the room of origin. To assess this result, flame temperature was defined as visual products of combustion transported by fire gases at 1,500°F (815°C) measured at the virtual thermocouples in the egress path. Figures 32 and 33 represent this data. While the peak ceiling temperature in the sprinklered area was measured at 356°F (180°C) in the sprinklered building and 662°F (350°C) in the non-sprinklered building, the model runs in both configurations produced temperatures substantially lower than the designated limit.

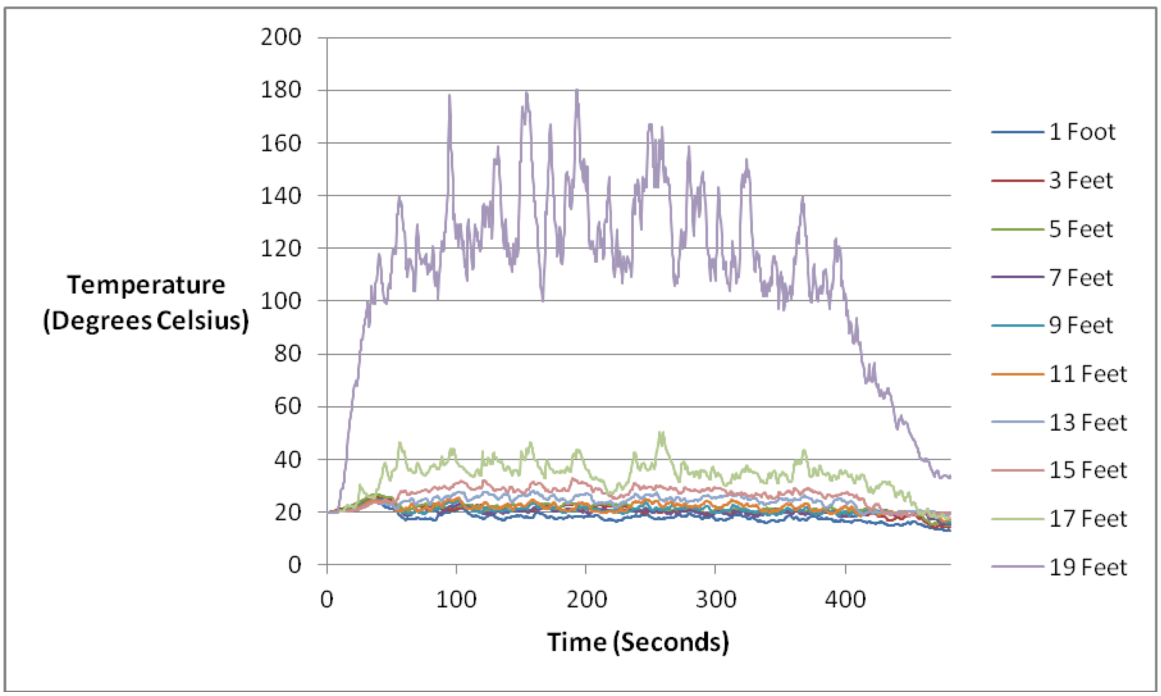

Figure 32. Courthouse Lobby Egress Path Temperatures (Sprinklered)

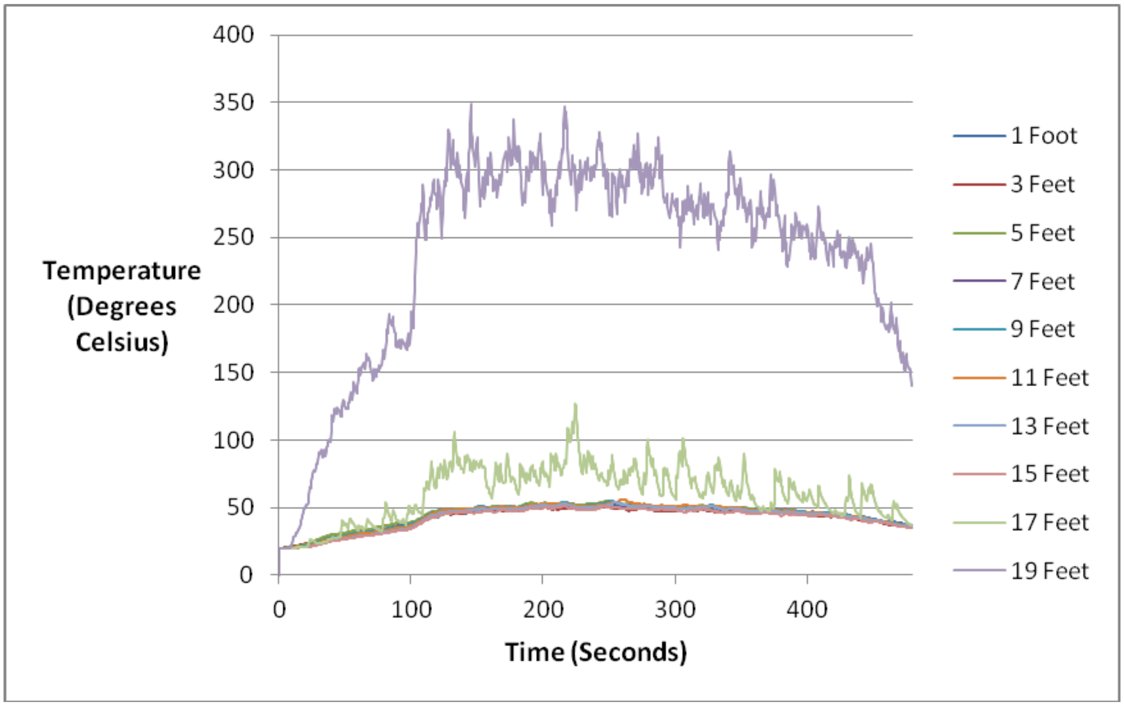

Figure 33. Courthouse Lobby Egress Path Temperatures (Non-sprinklered)

The purpose of the modeling analysis was not to validate any particular design, but to illustrate how modern fire modeling tools, such as the FDS and *Smokeview*, can be employed to perform pre-design and construction analysis to evaluate not only threats, but analyze a variety of proposed permanent countermeasures. In the examples shown, the quantified threat was defined by a sample of expert fire investigators who described a plausible fire threat scenario. This threat scenario was applied in the model to four different configurations using automatic fire sprinkler protection as the designated permanent countermeasure. Table 49 summarizes the results of the model outputs comparing the permanent countermeasures to the three legally mandated fire safety performance objectives.

Table 49. Fire Modeling Test Result Summary

		Prevent Flashover	Limit Fire Size	Confine Flames to Room of Origin
Small Office	Sprinklered	Pass	Pass	Pass
Small Office	Non-sprinklered	Fail	Fail	Pass
Courthouse Lobby	Sprinklered	Pass	Uncertain	Pass
Courthouse Lobby	Non-sprinklered	Pass	Fail	Pass

Modeling applications offer the ability to quantify the character of the data inputs. For the FDS and *Smokeview*, the building occupancy type, its construction materials and size, and the fire protection features can be defined in a virtual world and one or more threats applied to it. Altering any one of these variables can provide outputs against which permanent countermeasures can be assessed.

E. SUMMARY

The mixed methods research approach provided a multi-focused picture of several factors that must be considered to conduct a thorough policy analysis. Results from the national fire incident data analysis, the thematic content analysis, the Delphi survey of fire service professionals, and the fire modeling scenarios, provided a variety of data sets that enabled agglomeration of their results to better interpret the elements that comprise the *Physical Security Criteria for Federal Facilities* standard and the DBT to conduct a more complete policy analysis. The modeled scenarios, given a clear set of inputs, provide persuasive data outputs and illustrations that can explain how proposed protective countermeasures can be evaluated.

VIII. CONCLUSIONS AND RECOMMENDATIONS

As the nation's largest property manager, the federal government owns and maintains buildings and facilities in which its employees and visitors are subject to a variety of threats ranging from terroristic attacks to natural disasters. To enhance security against a variety of threat scenarios, the DHS ISC has created a *Physical Security Criteria for Federal Facilities* standard to reduce risk and consequences of unwanted threats. This standard uses a risk management assessment approach to determine levels of physical and operational protection expected to minimize the consequences of attacks. This thesis argues that the results collected through this risk management assessment devolve into past-practice prescriptive countermeasure solutions that may not be best suited to protect facilities and occupants from varied threats; and the use of performance-based design methods could help FSC address identified threats with custom solutions.

A. RESEARCH CONCLUSIONS

1. Primary Research Question Answered

The primary research project focused on one threat identified in the DBT document that accompanies the *Physical Security Criteria for Federal Facilities*, the arson scenario in which "an adversary places an improvised incendiary device (IID) containing an accelerant and utilizing a delay mechanism adjacent to a facility, but outside the view of security countermeasures" to determine how performance-based design methods could evaluate the effectiveness of the *Physical Security Criteria for Federal Facilities* permanent countermeasure options to arson threats.

The fire data research element showed that overall, federally owned, and occupied buildings and facilities perform well when threatened by accidental or intentional fires. Over a three-year study period, 86.4% of fires in federal office buildings were confined to the room or object in which the fire started, compared to 18.1% of the non-federal office buildings. Similarly, in federal courthouses, fires were contained to the room or object of origin 33.1% of the time, compared to 8.1% in non-federal courthouses. Additional

research is warranted to identify factors influencing the outcomes[116] between federal and non-federal properties. However, given the comparative success of containing fires to the object or room of origin in conjunction with the preponderance of accidental ignition sources in federal buildings,[117] it appears the "applicable construction [and life safety] standards" cited in the *Physical Security Criteria for Federal Facilities* and the DBT are adequate to satisfy the primary goal of life safety and the secondary goals of property protection and environmental controls.

The thematic analysis of the use of performance-based design as a countermeasure to arson threats was less definitive. Evidently, performance-based design has not been given significant consideration in the international literature as a means to design buildings and fire protection features to protect from an arson attack. In a review of 150 articles on the subject of performance-based design for fire safety, slightly more than two-thirds of the authors did not mention its suitability against incendiary fires. More significant, however, was the emphasis on scenario design. Nearly 71% of the authors who evaluated its effectiveness to counter incendiary threats stressed the importance of well-defined design fire scenarios. This thesis has argued the *Physical Security Criteria for Federal Facilities* arson scenario[118] is too vaguely defined for the development of effective countermeasures. The thematic analysis results support this hypothesis.

The Delphi survey approach produced an arson threat scenario quite different from that described in the *Physical Security Criteria for Federal Facilities.* Rather than using an accelerant-based IID with a timing device, the experts developed a scenario in which an adversary simply breaks into the building or facility and employs makeshift aids (e.g., waste paper, garbage, other combustible materials at hand) to fuel a fire. To enhance the value of this scenario as an element in a performance-based design, it must

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[116] Among others, factors could include the existence of automatic fire detection and suppression systems, fire resistive construction with automatic opening protectives (e.g., fire doors and dampers), aggressive enforcement of safety rules and regulations, or an employee culture commitment to maintaining a safe working environment.

[117] Only 5.4% of fire incidents were malicious.

[118] In which "an adversary places an improvised incendiary device (IID) containing an accelerant and utilizing a delay mechanism adjacent to a facility, but outside the view of security countermeasures."

be improved by additional qualification and quantification to describe better the location of where the fire was set in relation to walls, ceilings, doors or windows, as well as have a more specific description of the type and amount of combustible materials ignited.

Finally, the results of the fire effects modeling exercises show that by quantifying the criteria for both the design fire scenario and countermeasure features (e.g., construction type, fire protection features, fuel controls), a blind prediction of outcomes that meet federal fire safety requirements can be obtained.

2. Secondary Research Questions Answered

In addition to the primary question of the applicability of performance-based design methods to federal building and facility protection, this thesis included three secondary research questions.

- How can the arson threat scenario described in the DBT be quantified for the purposes of selecting permanent countermeasures?

As shown in the results of the thematic literature review, the quantification of the design fire scenario is critical to the evaluation of the modeled results, including countermeasures. The DBT arson scenario in which "an adversary places an improvised incendiary device (IID) containing an accelerant and utilizing a delay mechanism adjacent to a facility, but outside the view of security countermeasures" would be quantified by defining input parameters, such as the type and amount of accelerant, description of the facility construction, and spatial relationship of the IID to the facility. For example, the scenario could be rewritten "an adversary places an improvised incendiary device (IID) containing five gallons (19 L) of gasoline and utilizing a delay mechanism on an asphalt surface six inches (152 mm) from a 24-foot (7315 mm) exterior wall comprising four-inch (102 mm) brick installed over 10 mil moisture barrier applied to 0.625-inch (15.9 mm) oriented strand board supported by two by four-inch (51 by 102 mm) and clad on the interior with 0.625-inch (15.9 mm) Type-X gypsum wallboard, but outside the view of security countermeasures. The IID is placed 36 inches (914 mm) beneath a sealed vinyl frame window measuring 42 inches (1,067) wide by 48 inches (1,219 mm) tall." While the latter scenario details require extra effort to account for each

potential condition, in terms of fire safety performance, it provides the information needed to perform a successful blind prediction of the consequences the IID would have on the building or facility.

- Are the design methods published in the SFPE's *SFPE Engineering Guide to Performance Based Fire Protection* or the ICC's *Performance Code for Buildings and Facilities* suitable tools to evaluate permanent countermeasure options to quantified arson threats?

Although the thematic literature review showed little recognition by name of these two documents,[119] substantial concordance existed with the design methods employed by the SFPE and ICC. Figure 5 represents the SFPE performance-based design process. The fire modeling exercise used in this thesis integrated this process to the extent necessary to test the hypothesis of design fire quantification.

An added advantage of the performance-based design approach is its use of validated models to simulate a variety of events, and provide outputs in graphical and visual renderings that can be easily explained by qualified people. Input variables on the models can be altered and run at relatively little cost until the desired output is achieved.

While the nomenclature of the SFPE performance-based design process differs from the *Physical Security Criteria for Federal Facilities* risk assessment model, it employs similar principles: defining scope, identifying goals and objectives, performance criteria, and developing scenarios and trial designs (countermeasures). The significant difference between the two is the *Physical Security Criteria for Federal Facilities* standard relies on prescriptive countermeasures for an unlimited variety of threat scenarios, whereas the SFPE performance-based design process allows stakeholders to define the threats and customize temporary or permanent countermeasures.

- Should the ISC reports *Physical Security Criteria for Federal Facilities* and the DBT be limited to criminal or "manmade" threats as stated in the documents?

Over time, the GSA, which is responsible for the construction and maintenance of non-military and non-postal federal property, is moving from a solely prescriptive design

[119] Only 0.7% of respondents mentioned the SFPE engineering guide by title and one doctoral dissertation referenced the ICC code.

and construction approach to encouraging the precepts of performance-based design. The GSA *Facilities Standards for the Public Buildings service (P100)* embraces performance-based design alternatives.

Given the number, nature, and consequences of fires in federal facilities since 2007 (Tables 31 through 35), the GSA construction standards perform well compared to non-federal properties. In 86.4% of the fires in federal office buildings, and 33%[120] of the fires in federal courthouses, the fire was contained to the room or object of origin; thus meeting one critical condition of the GSA's federal fire safety regulations. If the criminal or "manmade" design threat scenarios in the DBT were quantified using performance-based design methods, keeping the *Physical Security Criteria for Federal Facilities* emphasis on criminal or "manmade" threats is appropriate.

B. STUDY LIMITATIONS

The following limitations on this study are acknowledged.

First, the Delphi survey to assess the likelihood of the arson scenario published in the DBT was conducted among a small population of fire investigation experts, N=18. The distribution of the results shows that respondents were equally divided between the scenario being unlikely or likely, with a small percentage (16.7%, n=3) reporting the scenario to be highly likely. The survey enabled the experts to develop an alternate arson scenario based on their experience and opinion.

To enhance the validity of the Delphi survey and its results, a larger population should be studied. The population should be geographically and experientially diverse, and likely have a high degree of skill in collecting and analyzing fire incident data.

Second, the data assumptions created for the two modeling scenarios were selected arbitrarily and based on a subjective basis regarding the construction, content, use, and occupancy of a so-called typical federal office space and courthouse lobby. The criteria were used solely to demonstrate the use of the fire effects modeling as an analysis

[120] In federal courthouse fires, N=6; therefore, so the data set is extremely small for conducting meaningful analysis.

tool, and no claim is made that the scenarios represent real conditions that may be found in these occupancies. To conduct fire effects modeling with a lesser degree of uncertainty, the data inputs should be collected from full-scale examples. Results of the fire effects models that contend to represent real world scenarios should be peer reviewed by qualified scientists and engineers with experience in fire behavior and modeling. As Rein et al. (2011) expressed in their Dalmarnock, Scotland studies, even the possession of good input data may not result in the fire effects model representing it accurately.

Finally, while altruistically the ultimate social goal is life safety, employee and visitor safety, or survival were not addressed in this study. Data on employee and visitor population and characteristics was not available; therefore, the study was limited to arson attack modes that could occur whether the building or facility was occupied or not. Additionally, results from the Delphi survey suggested the most likely arson scenario occurred when the building was not occupied or was occupied after hours by only a very small population, such as maintenance or housekeeping personnel.

C. IMPLEMENTATION ISSUES

The ISC *Physical Security Criteria for Federal Facilities* interim standard was issued April 12, 2010 for a 24-month validation period. That deadline has passed. To implement the policy recommendation made below, the ISC will have to review the proposed policy and consider reopening the validation period while it tests and validates the proposed methods.

D. ISSUES FOR FUTURE RESEARCH

Although rich and diverse sources of literature on building construction, fire protection, performance-based designs, federal facilities, and terrorist threats are avaible, significant gaps worthy of additional research remain. This thesis suggests the following topics for future research.

1. Fire Effects Modeling for the Sample Scenarios

The two building fire scenarios employed in this thesis were selected solely to demonstrate the use of fire effects modeling as one tool that can be employed to evaluate permanent countermeasure proposals against asymmetric threats.

Sample physical world federal office and courthouse facilities should be surveyed to collect data on construction, fuel load, fuel array, use, and occupancy for the purpose of conducting fire effects modeling analysis of permanent countermeasures already in place or proposed as part of the ISC facility security level assessments.

2. Data Collection, Management and Analysis

Considering the number, size, and value of federal government real property assets, comprehensive studies of fire and/or arson incidents and their impact on both physical property and continuity of operations are in order. It is remarkable that the GSA, the government's largest non-military and non-postal property manager, has no meaningful instrument to collect and analyze fire and/or arson incidents, especially since it has been more than 10 years since the GAO identified this shortcoming.

Additional research should be conducted to develop a data collection, management, and analysis instrument for federal buildings and facilities, or the GSA should work with the USFA NFDC to develop a "special reports" category unique to federal assets that could be appended to the existing NFIRS.

3. Design Fire Scenarios

An unending need exists for additional research on worst-case design fires, such as the use of accelerants and IIDs to quantify both the inputs and consequences. While the literature on design fires continues to grow, full-scale fire testing is time-consuming and expensive. Fire tests often are driven by propriety needs to develop specific fire protection countermeasures in government, business, and industry. A large-scale project,

perhaps funded by the federal government, would be useful to create a repository of design fire data that could be used for performance-based design applications in federal and non-federal buildings and facilities.

Furthermore, the specific scenario in this thesis of the two-story sprinklered courthouse atrium needs additional study and analysis to determine whether automatic sprinkler protection can perform as a suitable countermeasure to an accelerated fire by keeping the HRR under 950 Btu/sec (1,000 kW or 1 MW).

4. Application of Fire Models to Worst Case Catastrophic Design Fires

Concurrent with full-scale fire testing, research should be conducted to measure the validity of existing fire effects models—or to develop new ones—that can provide consistent and reliable blind predictions of catastrophic design fires. As asymmetric homeland security threats evolve, criminals, or terrorists are likely to adapt their destructive methods to exploit vulnerabilities in the built environment (Leiter et al., 2012). The federal government has an interest in maintaining current data analysis tools to protect its human and inanimate assets.

5. Real Property Tenancy and Ownership

The fire incident data accumulated for this study shows that a significant difference exists in fire outcomes between federally owned and occupied real property and all others. Does tenancy or ownership make a difference in fire prevention and protection? Does the fact federal buildings are under single managerial control affect fire incidents and outcomes?

Research to explore the nature of fires in federal buildings and facilities could be used to identify important fire safety solutions that could be transferred to the public at large to reduce potentially the significant fire-related loss of life and property that occurs in the United States.

6. Fire Sprinkler System Maintenance and Reliability

In nearly all the modeled events, the automatic fire sprinkler systems controlled the fires and kept the results within the parameters of the GSA's federal fire safety regulations. During a four-year study, the NFPA found that where office buildings[121] were protected by automatic sprinkler systems, the systems operated effectively 95% of the time and confined the fire to the room of origin in 94% of events (number of reported fires = 1,170) (Hall, 2010b). In those cases where the sprinklers failed to control the fire, 64% of the failures were attributed to the systems being shut off, 17% due to lack of maintenance, and the balance were the result of a variety of other impairments (Hall, 2010b). Given the success rate of properly operating sprinkler systems, research should be conducted on methods to enhance system reliability through regular inspection, testing and maintenance, and the implementation of impairment control programs. The technical response of sprinkler effectiveness seems evident; the research should be conducted to identify human failures that resulted in ineffective performance.

7. Perimeter Security Enhancements

Results from the Delphi survey of fire investigation experts indicated a strong correlation between opportunistic break-ins and fires in federal buildings. Additional research on the efficacy of perimeter security countermeasures may yield data recommending added protection from adversaries through enhanced human, visual, kinetic, or other technological security regimes, which may prove to be a cost-effective solution to fire threats, if prompt response from law enforcement or facility security personnel can interrupt these attacks.

8. Federal Building Safety Analysis

A key theme of this report is the need to improve the level of detail and definition so event outcomes can be measured. One area that could use improvement is in the federal building safety analysis, 41 CFR 102-80.115, that states fire protection strategies

[121] The study included no data for courthouse buildings, nor does it discriminate between federal or non-federal properties.

are deemed successful if the selected method is able to keep flames in the room of origin. As discussed in some detail in the pass-fail criteria of the previous unit, the varying interpretations of flame characteristics and their consequences may result in inconsistent application of this criterion. Since flames represent visual constituents of products of combustion, and perhaps more importantly, are dramatically thermodynamic, the determination of whether the flames left the room of origin is highly subjective based on the viewers' perception. According to the CFR criteria, even if a transient flame left the room of origin but had no consequence on people or objects, the fire safety strategy would not be rendered successful.

Furthermore, the conditions under which the room enclosure exists at the time of fire ignition should be defined. Flames are more likely to leave a room with open vents (windows or doors) than one in which these vents are closed.

9. Performance-Based Design Applications to Other Threats

This thesis contends that given adequate scenario information, performance-based design methods can effectively proposed and evaluate temporary or permanent countermeasures against arson threats. Can the design methods be applied to other threats? Given the 31 different threat scenarios outlined in the DBT, it would be well to know if the performance-based design methods are universally applicable to a growing and varied number of threat conditions.

Furthermore, existing deterministic modeling software packages for fire and life safety analysis have not been validated for other threat scenarios. Research should be conducted to inventory and analyze for effectiveness the wide variety of modeling products that exist to address specific threats, such as explosive and IED blasts, vehicle-borne improvised explosive devices, CBRN dispersion, bio-contamination and vector distribution, infectious disease communicability, and even network and supervisory control and data acquisition (SCADA) cyberthreats.

E. POLICY RECOMMENDATION DERIVED FROM CONCLUSIONS

The DHS ISC's 2012 *Physical Security Criteria for Federal Facilities* standard establishes a baseline set of physical security criteria to be applied to federal buildings and facilities under its jurisdiction. It uses a risk assessment model (Figure 3) to guide users through a decision-making process for evaluating the levels of building and facility protection from a variety of threats. The foundation of the risk assessment model is found in a "Facility Security Level" score derived from the 2008 standard Facility Security Level Determination for Federal Facilities. That analysis produced a "Facility Security Level" score from I to V (low to critical) depending upon the facilities' mission criticality, symbolism, population size, and threat to tenant agencies. The later document, the *Physical Security Criteria for Federal Facilities* standard, provides little guidance other than a table of prescriptive solutions on how to evaluate the identified threats and develop meaningful countermeasures.

The adoption and application of performance-based design methods—including qualification and quantification of the threats, and clear articulation of the existing or proposed countermeasures—would provide those responsible for risk assessment blind predictions of potential outcomes. Consequently, a revised ISC risk assessment model is proposed to incorporate the precepts of performance-based design at two decision points in the process (see Figure 34: Proposed ISC Risk Assessment Model). In the suggested model, performance-based design methods are added at Step 3 (Determine the LOP needed to meet risk) and Step 5 (Determine the highest achievable LOP). Results from well-qualified and quantified performance-based design analysis would provide decision makers on the federal FSC (or even those in the design and procurement process) a level of confidence in the existing LOP or the proposed interim and permanent countermeasures because their performance has been evaluated against specific threats.

The *Physical Security Criteria for Federal Facilities* standard risk assessment model (Figure 3) compels the FSC to identify and assess risks (e.g., threat plus consequence plus vulnerability) against all the 29 so-called "undesirable events" listed in the standard. The companion document, the DBT , includes 31 threat scenarios, some of

which overlap the “undesirable events” list. These scenarios (Appendix B) have been shown to be so vague that an effective evaluation of countermeasures is impossible.

Step 3 in Figure 34 is a decision point where the FSC is compelled to choose if the existing LOPs (countermeasures) are commensurate with the risk. The only guidance provided to the FSC is “the security organization should determine whether the countermeasures contained in the baseline LOP [levels of protection] adequately mitigate known or anticipated risks to the facility” (U.S. Department of Homeland Security, 2010b, pp. 21–22). By adequately quantifying the anticipated threats and the known countermeasures (e.g., existing conditions), and employing suitable deterministic modeling software, the FSC could anticipate with some level of confidence the building or facility’s ability to resist the threats.

A second opportunity exists in the risk assessment model to employ performance-based design methods. At Step 5 in Figure 34, the FSC has determined that the existing LOP is inadequate and must determine what must be accomplished to accept or reject the risks. The performance-based design approach of: 1) qualifying and quantifying the design threat scenarios, 2) modeling design scenarios with proposed countermeasures, and 3) using the outcomes to evaluate performance in line with satisfactorily managing the risks, provides another opportunity for improved security.

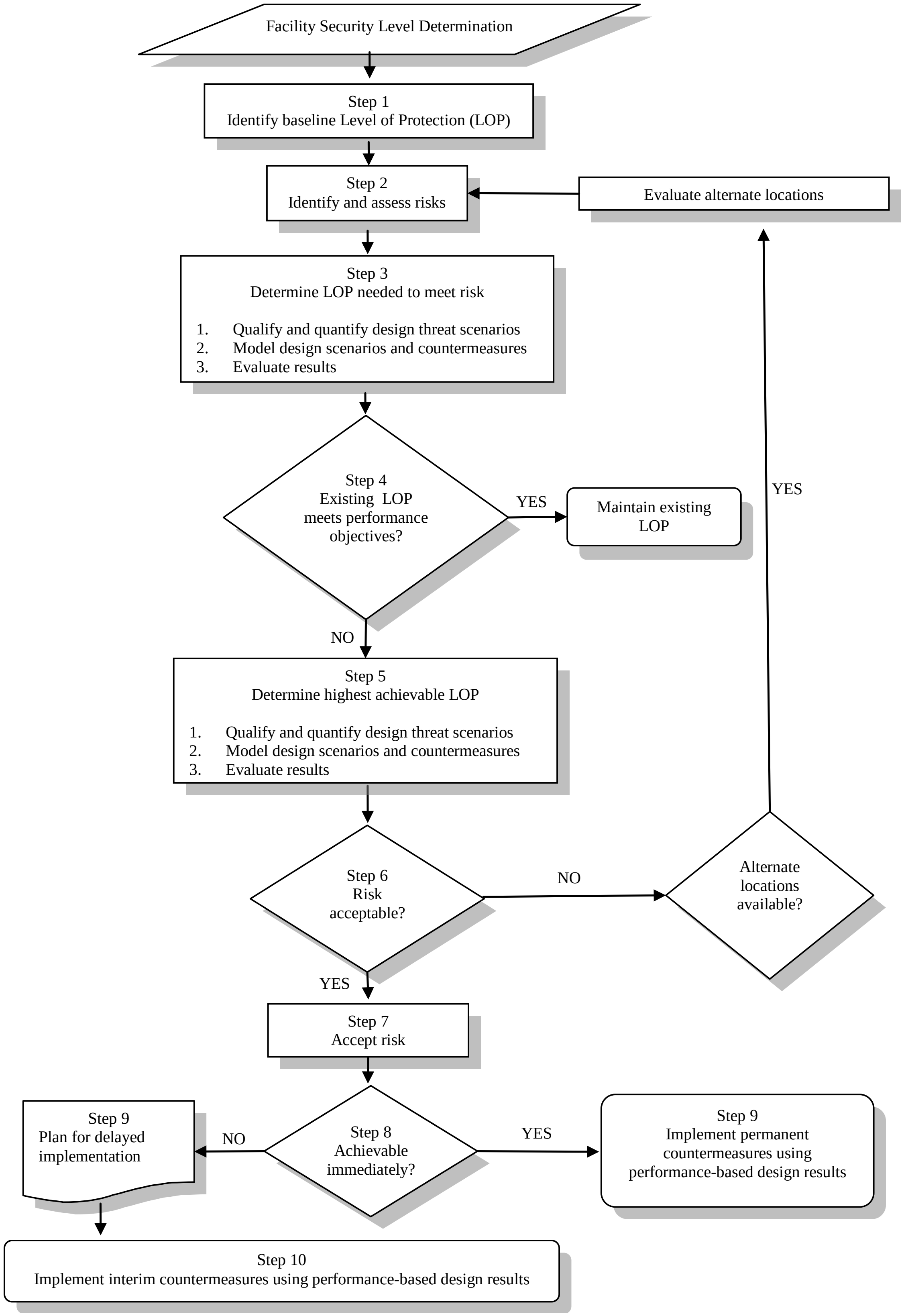

Figure 34. Proposed ISC Risk Assessment Model

F. CONCLUSION

This thesis evaluates the application of performance-based design methods to the *Physical Security Criteria for Federal Facilities* standard to address the specific threat of arson to federal buildings and facilities. It proposes a new model for physical security risk assessment that incorporates performance-based design methods at two decision points to help officials make rational judgments regarding security countermeasure based on an analysis of the proposed threat.

The strategic implications of this model for homeland security include, specifically, improving fire and life safety in federal buildings and facilities, and eventually providing a model construct for hardening federal targets from a variety of threats, enhancing federal continuity of operations, and strengthening national continuity of government in the face of unwanted criminal or terrorist attacks.

APPENDIX A. PUBLIC BUILDING DEFINED

The Administrator of General Services is responsible for the construction and maintenance of public buildings. According to Title 40, U.S.C. Subtitle II Part A Chapter 33 Section 3301, the term “public building” means a building, whether for single or multitenant occupancy, and its grounds, approaches, and appurtenances, which is generally suitable for use as office or storage space or both by one or more federal agencies or mixed-ownership government corporations.

In the law, public buildings include federal office buildings, post offices, customhouses, courthouses, appraisers’ stores, border inspection facilities, warehouses, record centers, relocation facilities, telecommuting centers, similar federal facilities, and any other buildings or construction projects that the President of the United States considers to be justified in the public interest.

The term does not include those building or construction projects on the public domain (including that reserved for national forests and other purposes); are on US government property in foreign countries; are on Indian and native Eskimo property held in trust; are on land used in connection with federal programs for agricultural, recreational, and conservation purposes, including research in connection with the programs; are on or used in connection with river, harbor, flood control, reclamation or power projects, for chemical manufacturing or development projects, or for nuclear production, research, or development projects; are on or used in connection with housing and residential projects; are on military installations (including any fort, camp, post, naval training station, airfield, proving ground, military supply depot, military school, or any similar facility of the Department of Defense); belong to installations of the Department of Veterans Affairs used for hospital or domiciliary purposes; or the President of the United States considers to be excluded from the public interest (Legal Information Institute, 2011c).

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APPENDIX B. UNDESIRABLE EVENTS AND DBT SCENARIOS

The DBT includes the following 31 threat scenarios (Table 50) to be used for threat analysis and countermeasure planning.

Table 50. Undesirable Events and DBT Scenarios

Undesirable Event	Design Basis Threat Scenarios
Aircraft as Weapon	Deliberately crashing a Cessna 172 Skyhawk (or similar) into a facility. The Cessna 172's characteristics are as follows: a) Maximum cruise speed: 126 knots (233 km/h) b) Maximum takeoff weight: 2,550 lbs (1157 kg) c) Useable fuel capacity: 318 lbs (144 kg) d) Full fuel payload: 523 lbs (237 kg) e) Range: 610 nm (1130 km) f) Height: 8 ft 11 in (2.72 m) g) Length: 27 ft 2 in (8.28 m) h) Wingspan: 36 ft 1 in (11 m)
Arson	An adversary places an IED containing an accelerant and utilizing a delay mechanism adjacent to a facility, but outside the view of security countermeasures.
Assault	Single assailant armed with a blunt weapon.
Ballistic Attack-Active Shooter	An individual enters a facility and begins to attack occupants using multiple handguns or a handgun and a rifle.
Ballistic Attack-Small Arms	An individual armed with a rifle fires indiscriminately at a facility from outside.
Ballistic Attack-Standoff Weapons	An individual assaults a large federal building using a homemade mortar using a fused explosive projectile.

Undesirable Event	Design Basis Threat Scenarios
Breach of Access Control Point-Covert	An individual enters a federal facility with a large group of visitors and displays a counterfeit identification badge.
Breach of Access Control Point-Overt	An adversary uses a handgun in an effort to breach security at the entrance checkpoint with the intent to proceed inside the facility.
CBR Release—External	A single adversary releases chlorine gas in the area of an air intake.
CBR Release—Internal	A single adversary releases Sarin gas by dispersing it in the lobby of a federal building.
CBR Release—Mailed or Delivered	An envelope containing Ricin is mailed to a facility.
CBR Release – Water Supply	One to three adversaries access on-site potable water supply piping at a valve without backflow protection and pump a highly lethal, tasteless, odorless agent into the system under pressure, or, At a facility with large water storage tanks or reservoirs, adversaries access the water supply and dump a non-lethal contaminant into the water.
Civil Disturbance	During a planned demonstration, a subset of protesters turns violent and uses available on-site materials to attempt to breach or damage the entrance to a facility.
Coordinated or Sequential Attacks	Assault by a team of 4–12 adversaries, each armed with an assault-style rifle and handgun. The assault may be of a suicidal nature and will also involve the use of small IEDs.
Disruption of Building and Security Systems	One to three adversaries gain access to the power supply to several of the building’s Closed Circuit Television (CCTV) cameras with the intent to disable the cameras.

Undesirable Event	Design Basis Threat Scenarios
Explosive Device—Mailed or Delivered	A package approximately the size of a shoebox containing a pipe bomb is initiated by opening the package. The pipe bomb will be Polyvinyl Chloride (PVC)-pipe to reduce weight, and contain approximately two pounds of black or smokeless powder. The device will also contain added shrapnel, such as nails or metal ball bearings. Black or smokeless powder has an approximate TNT equivalency factor of 0.55. Two pounds of black powder would have a TNT equivalency of 1.1 pound of TNT.
Explosive Device—Man-portable External	A device concealed in a backpack is placed near an entrance to a facility. The IED will consist of approximately four pounds of black or smokeless powder in galvanized pipe bombs. The devices will also contain added shrapnel, such as nails or metal ball bearings. The device may also contain steel plates to direct the force of the explosion towards the entrance. The device will be detonated by a timer mechanism. Black or smokeless powder has an approximate TNT equivalency factor of 0.55. Four pounds of black powder would have a TNT equivalency of 2.2 pound of TNT.
Explosive Device—Man-portable Internal	A device concealed in a backpack is placed on a public area inside a facility. The IED will consist of approximately four pounds of black or smokeless powder in galvanized pipe bombs. The devices will also contain added shrapnel, such as nails or metal ball bearings. The device may also contain steel plates to direct the force of the explosion towards the entrance. The device will be detonated by a timer mechanism. Black or smokeless powder has an approximate TNT equivalency factor of 0.55. Four pounds of black powder would have a TNT equivalency of 2.2 pound of TNT.

Undesirable Event	Design Basis Threat Scenarios
Explosive Device—Suicide/Homicide Bomber	A suicide/homicide bomber enters an occupied public space in the facility and detonates a suicide vest. The device consists of five pounds of TNT-equivalent explosive, activated by a switch carried by the adversary. The type of explosive is known to vary widely. The device will also contain added shrapnel, such as nails, screws, nuts and bolts, or metal ball bearings.
Explosive Device—Vehicle-Borne IED	In a location in which vehicles are <u>not</u> subject to screening for VBIEDs, a passenger sedan with an ammonium nitrate-based charge of 200 pounds of TNT equivalency concealed in a trunk, initiated by a timer or other delay mechanism, such as a fuse. In a location in which vehicles are subject to screening for VBIEDs by use of physical inspection of the trunk, passenger compartment, undercarriage, etc., a passenger sedan with an ammonium nitrate-based charge of 50 pounds of TNT equivalency concealed in sealed void spaces (door panels, gas tanks, etc.), initiated by a timer or other delay mechanism. The ammonium nitrate mix is known to vary, which may result in substantially different TNT equivalency factors.
Hostile Surveillance	Adversaries utilize the Internet to obtain open source material on a potential target, and a team of two conducts surveillance from a nearby pubic location to observe specific operational details of the target in preparation for a possible attack.
Insider Threat	Insider threat acts include a broad range of acts, from secretive acts of theft or subtle forms of sabotage to more aggressive and overt forms of vengeance and sabotage. The coordination of insider threats in perpetration of any other undesirable events is likely to lead to a greater chance of success.

Undesirable Event	Design Basis Threat Scenarios
Kidnapping	Two adversaries with handguns attempt to abduct a senior federal employee from a parking lot area, or, In facilities with a childcare center, an unarmed, non-custodial parent attempts to enter a controlled area and abduct a child.
Release of On-site Hazardous Materials	An adversary accesses external storage tanks of hazardous materials and manipulates valves or connections to create a leak.
Robbery	Single assailant armed with a semi-automatic handgun confronts an employee at a cash window (or similar disbursement location where valuables are stored), or, Single assailant armed with a knife confronts an employee approaching his vehicle in the rear parking lot of the facility.
Theft	Single perpetrator authorized to have access, using stealth to obtain and conceal the property while removing it from the facility.
Unauthorized Entry—Forced	Two adversaries, equipped with hand tools, including crowbars, hammers, channel locks, vise grips, and screwdrivers.
Unauthorized Entry—Surreptitious	A single adversary gains entry to a facility through an unsecured door or window. The adversary is capable of accessing a second-story window or one-story roof by using available means to climb.
Vandalism	Unknown adversaries painted graffiti on facility walls or external assets.
Vehicle Ramming	A 4,700-pound pickup or sport utility vehicle traveling at 35 miles per hour attempts to ram into a facility.

Undesirable Event	Design Basis Threat Scenarios
Workplace Violence	An employee under duress from a job-related situation enters the facility and assaults co-workers using a handgun, or, Co-workers in the office get into a verbal confrontation resulting in one physically assaulting the other.

APPENDIX C. CONVERSION FACTORS

Table 51. Common Conversion Factors for United States Customary to SI Units (From: Quintiere, 1998)

	United States customary units to SI	**SI to United States customary units**
Length	1 inch = 25.4 millimeter	1 millimeter = 0.0393 inch
	1 inch = 2.54 centimeter	1 centimeter = 0.3937 inch
	1 foot = 0.3048 meter	1 meter = 3.2808 feet
Area	1 $yard^2$ = 0.8361 $meter^2$	1 $meter^2$ = 10.7639 $feet^2$
Mass	1 lb = 0.4535924 kilogram	1 kilogram = 2.20462 lbs
	1 oz = 28.34952 gram	1 gram = 0.0022046 lb
Density	1 $pound^3$ = 16.0186 kg/$meter^3$	1 kg/$meter^3$ = 0.06243 pounds per $foot^3$
Energy	1 Btu = 1.055056 kiloJoule	1 kiloJoule = 0.94783 Btu
Heat	1 Btu = 1.055056 kiloJoule	1 kiloJoule = 0.94783 Btu
	1 calorie = 0.004168 kiloJoule	1 kiloJoule = 238.846 cal
	1 Btu = 251.9958 cal	1 calorie = 0.003968321 Btu
Heat release	1 Btu/hour = 0.2930711watt	1 watt = 3.4121 Btu/hour
rate	1 Btu/hour = 0.002930711kilowatt	1 kilowatt = 3412.1 Btu/hour
	1 Btu/hour = 2.930711e-007 megawatt	1 megawatt = 3,412,142 Btu/hour
Pressure	1 lb/ per $inch^2$ = 0.06804596 atmosphere	1 atmosphere = 14.69695 lbs/per $inch^2$
Temperature	1 degree Fahrenheit = (°C x 1.8)+32	1 degree Celsius = (°F - 32)/1.8

Table 52. Alternative Energy Units

1 British thermal unit (Btu) will raise 1 lb of water 1°F at 68°F
1 calorie (cal) will raise one gram (g) of water 1°C at 20°C

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APPENDIX D. LITERATURE REVIEW CODEBOOK

100-Literature Source:

101—Whole Book
102—Book, Section
103—Consumer Magazine
104—Professional Journal: peer reviewed
105—Trade Journal: fire service, building construction industry, architectural digest
106—Website
107—Conference Proceedings
108—Other

200-Year: Four-digit code for year document/article was published. (n.d., if no date provided)

300-Geocoding: The document/article pertains to circumstances specific to the nation listed.

301—Not specific to geographical location.
302—Australia
303—Canada
304—China/Hong Kong/Taiwan
305—Denmark
306—Finland
307—Japan
308—New Zealand
309—United Kingdom
310—United States
311—Other
312—Unknown: not stated.

Variables

Q1. Arson was mentioned in same article as performance-based design.

0. No
1. Yes

Q2 Performance based design was identified as a design solution for arson mitigation (e.g., permanent countermeasures).

0. No
1. Yes

Q3 If used as an assessment method, the proposed performance-based design solution was determined to be:

0. Not addressed/No assessment made
1. Unsuitable
2. Suitable
3. Situation dependent

Q4 If used as design method, keywords for the identified/needed facilitating criteria were:

Q5 If used as a design method, keywords for the identified impediments to using performance based design were:

Q6 The *SFPE Engineering Guide to Performance Based Fire Protection* was mentioned in article in relation to arson mitigation.

0. No
1. Yes

Q7 The International Code Council *Performance Code for Buildings and Facilities* was mentioned in article in relation to arson mitigation.

0. No
1. Yes

Q8 The *SFPE Engineering Guide to Performance Based Fire Protection* was identified as an arson mitigation design method.

0. No
1. Yes

Q9 The International Code Council *Performance Code for Buildings and Facilities* was identified as an arson mitigation design method.

0. No
1. Yes

Q10 If used as a design method, the application of the *SFPE Engineering Guide to Performance Based Fire Protection* performance-based design solution was determined to be:

0. Not addressed/No assessment made
1. Unsuitable
2. Suitable
3. Situation dependent

Q11 If used as design method, keywords for the identified/needed facilitating criteria were:

Q12 If used as a design method, keywords for the identified impediments to using performance based design were:

Q13 If used as a design method, the application of the International Code Council *Performance Code for Buildings and Facilities* performance-based design solution was determined to be:

0. Unsuitable
1. Not addressed/No assessment made
2. Suitable
3. Situation dependent

Q14 If used as design method, keywords for the identified/needed facilitating criteria were:

Q15 If used as a design method, keywords for the identified impediments to using performance based design were:

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